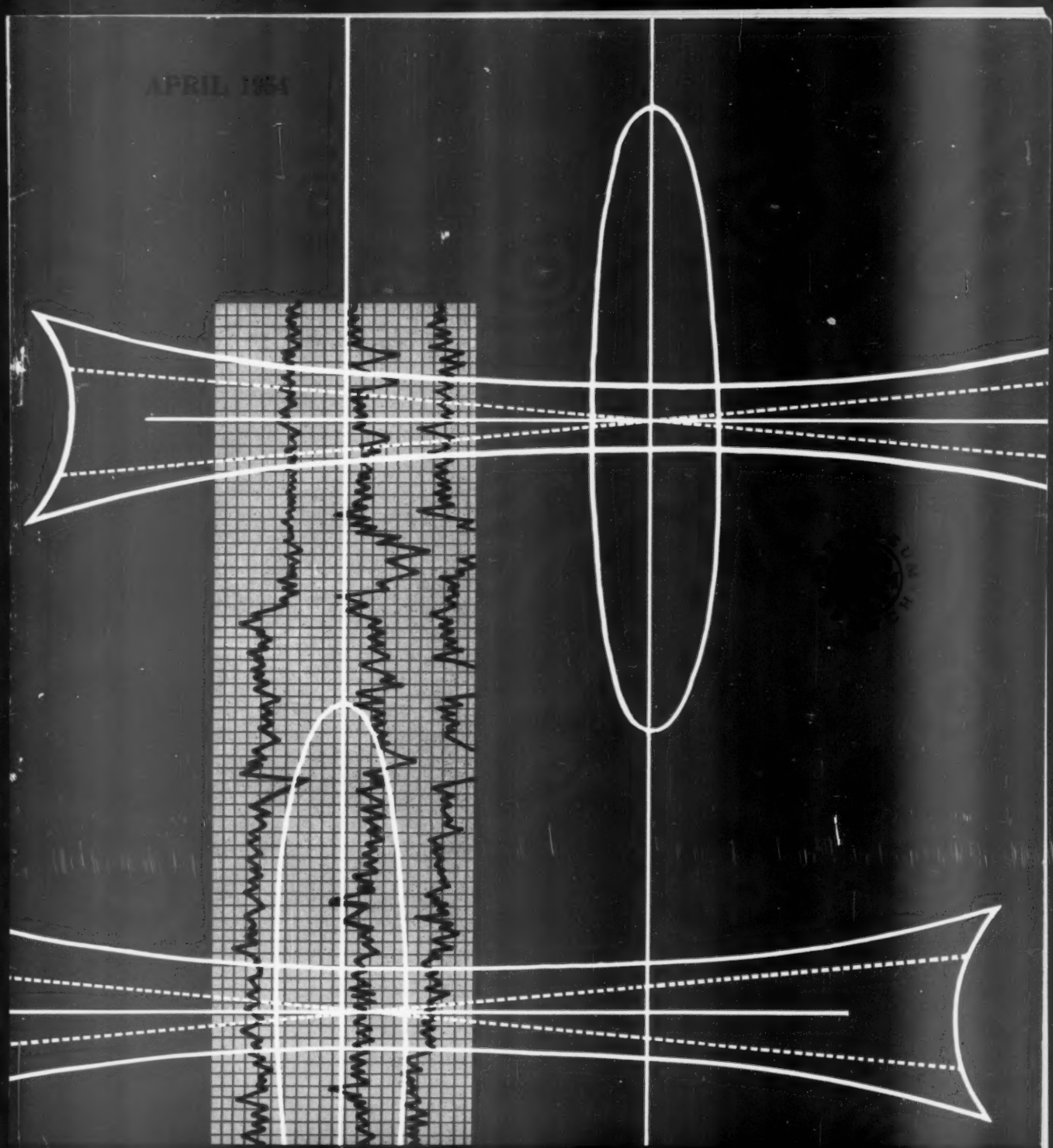
APRIL 1954



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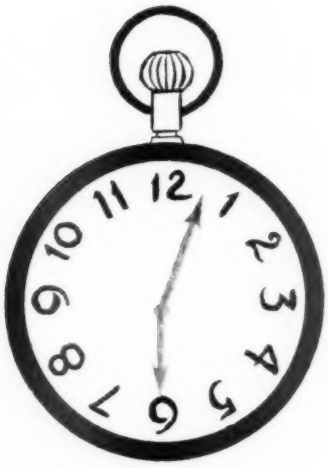

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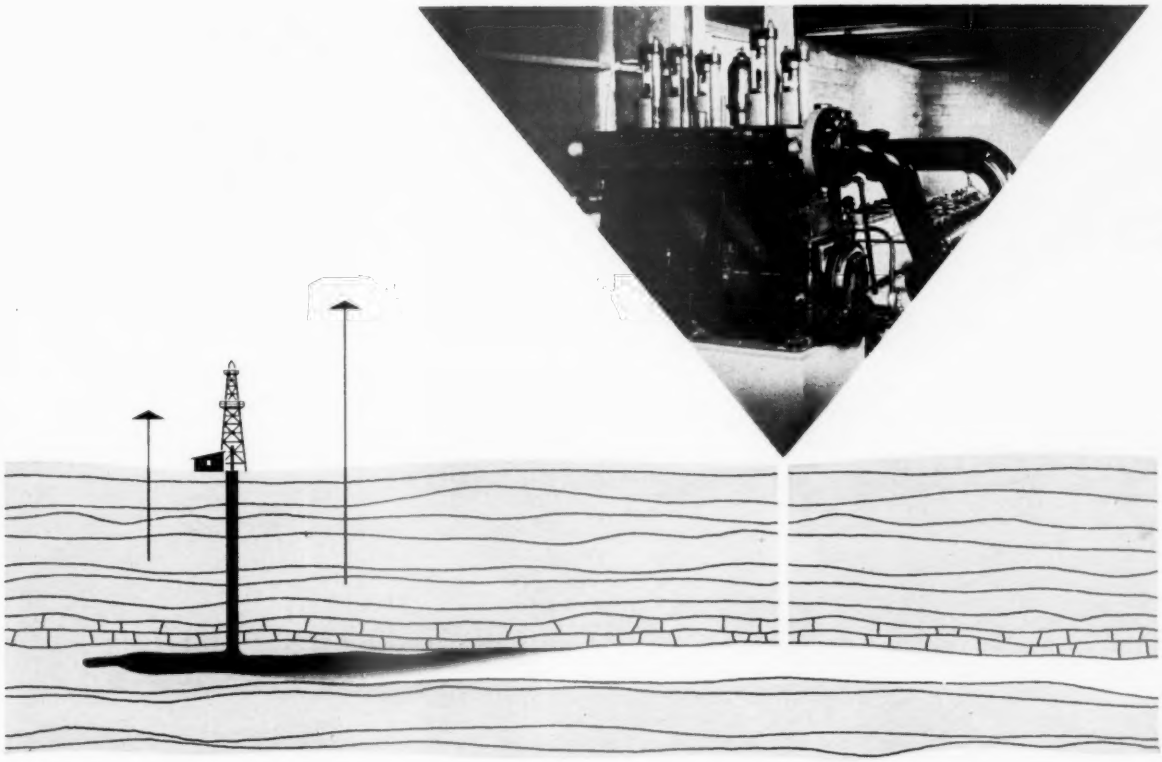

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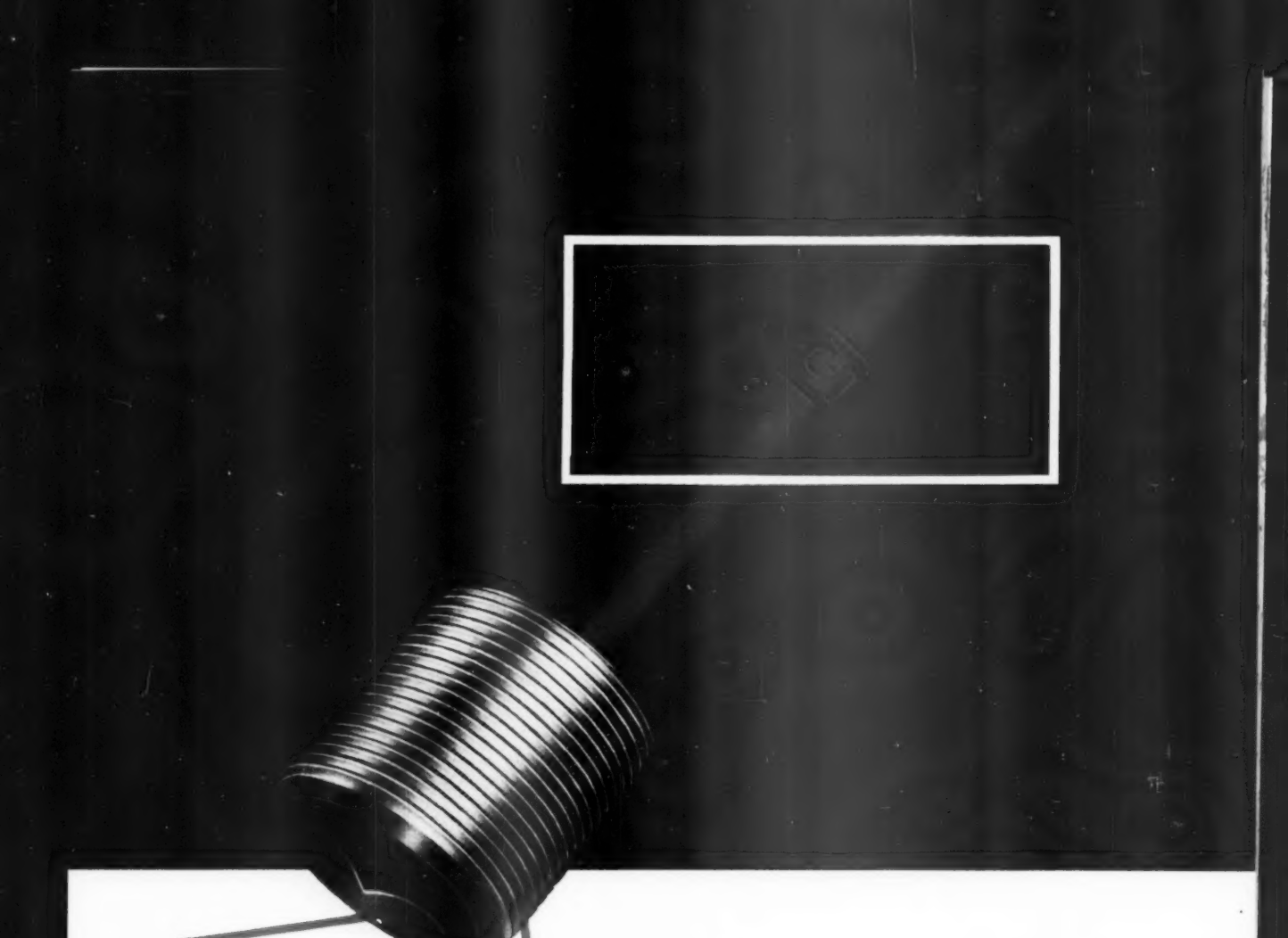

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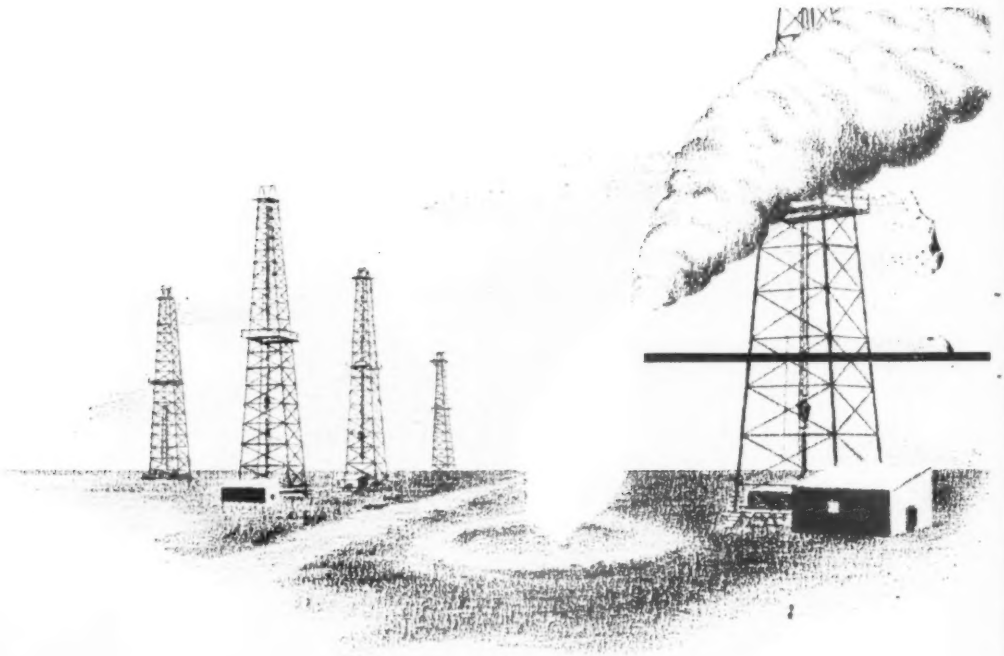

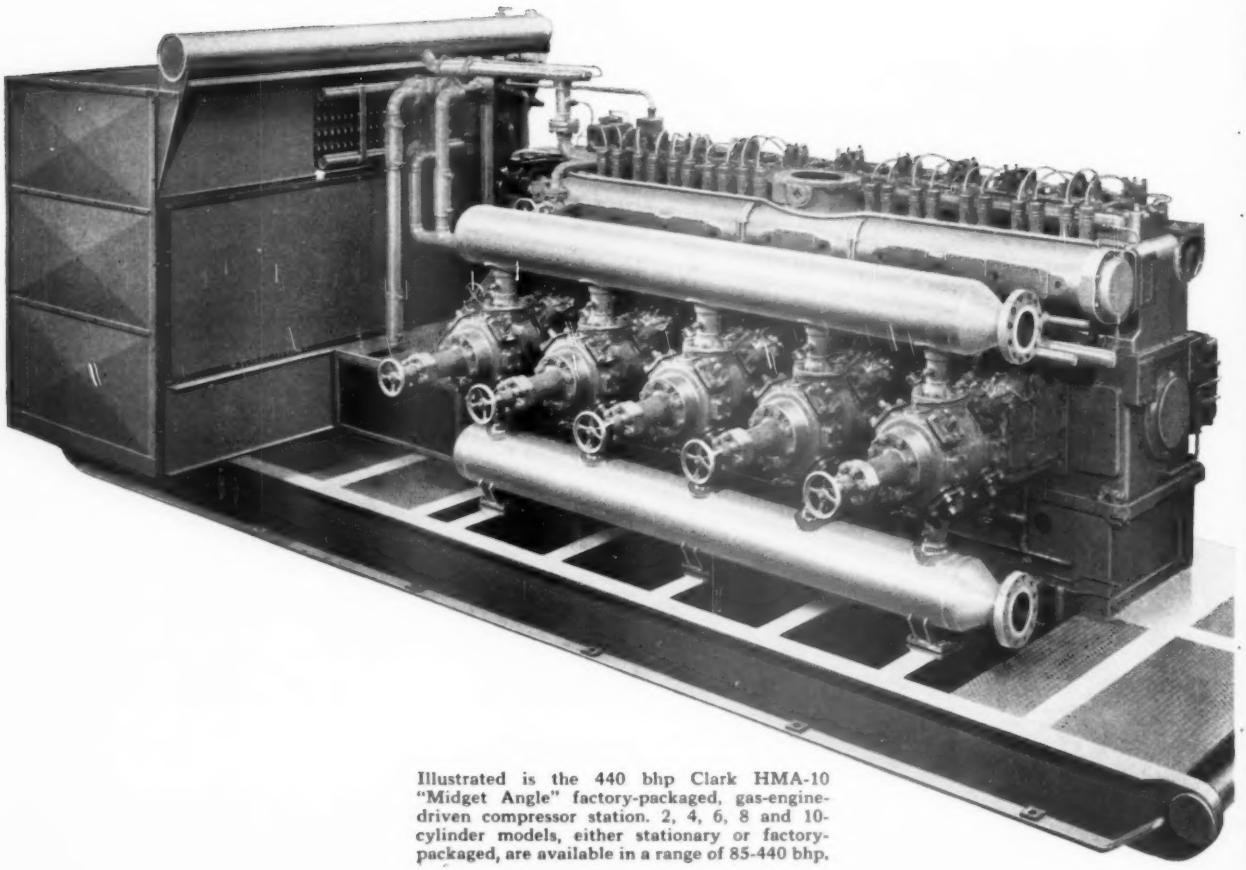

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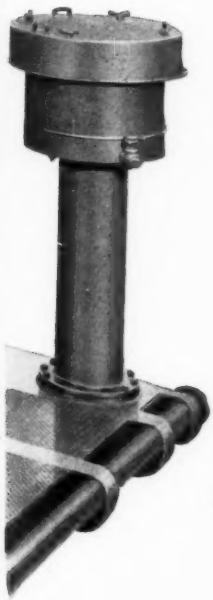

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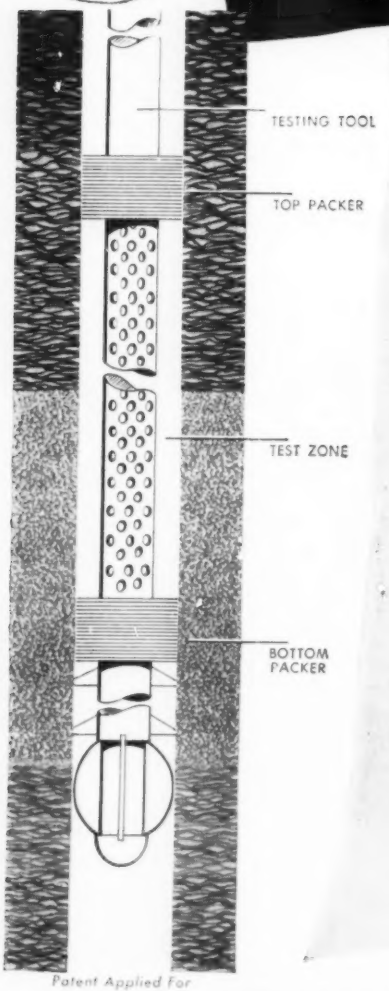

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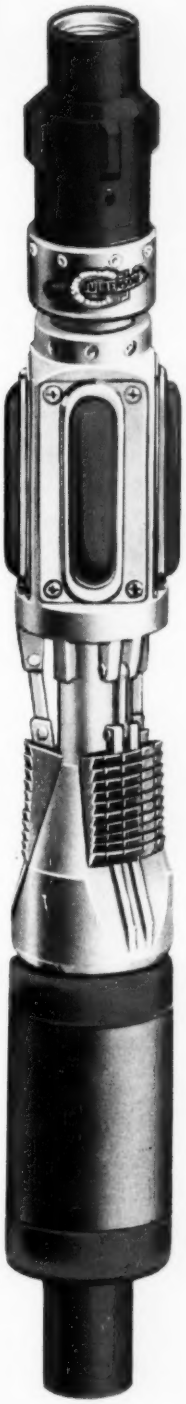

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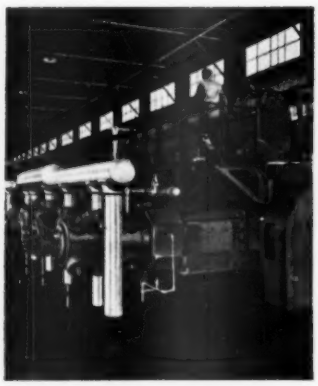

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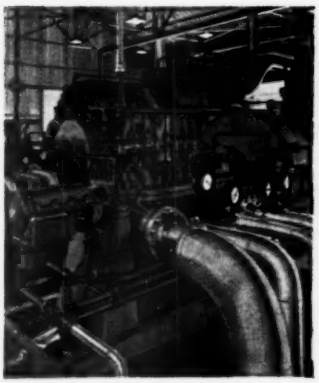

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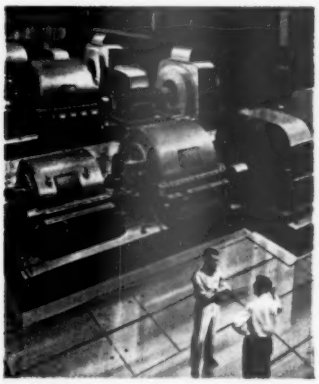

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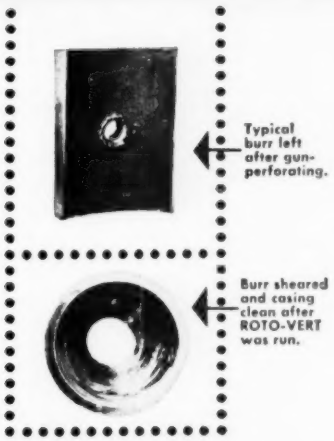
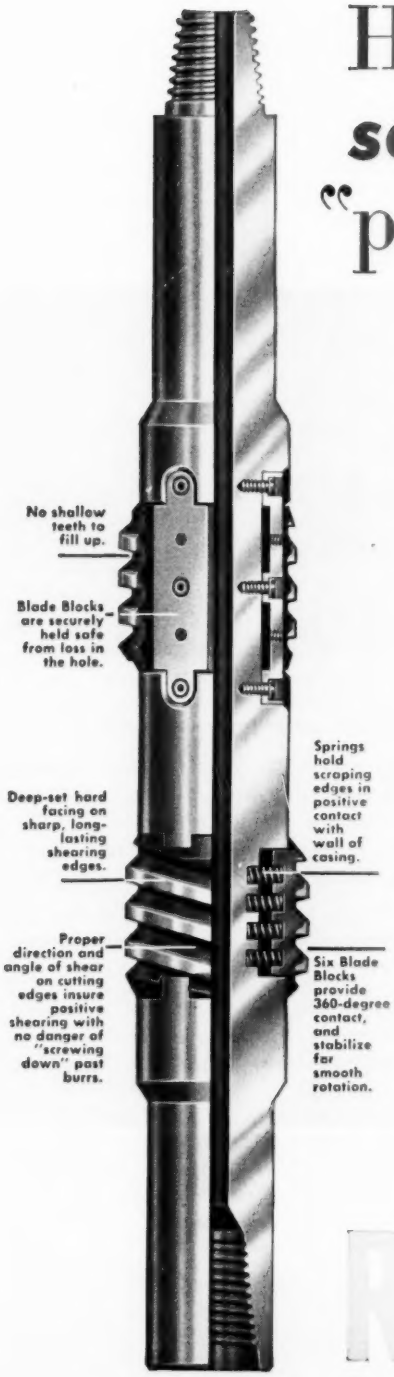


Here's why
SCRAPING YOUR CASING
"pays off"


No shallow teeth to fill up.
Blade Blocks are securely held safe from loss in the hole.
Springs hold scraping edges in positive contact with wall of casing.
Deep-set hard facing on sharp, long-lasting shearing edges.
Proper direction and angle of shear on cutting edges insure positive shearing with no danger of "screwing down" past burrs.
Six Blade Blocks provide 360-degree contact, and stabilize for smooth rotation.

Unless the inside of your casing—the vital "working surface"—is clean and smooth, there is always a possibility of trouble in future operations. Burrs from gun-shot perforations, hardened cement or mud, and even mill scale are all dangerous when the time comes to run testers or swabs, or to set retainers or packers of any description.

The Baker Model "C" ROTO-VERT Casing Scraper removes undesirable obstructions from the inside of the casing, leaving it clean and smooth. Burrs or imbedded bullets are sheared away; cement, mud and scale are scraped away, so that any down-hole work can be safely done at once, or during the years to come.

SCRAPE WHILE DRILLING OUT

The ideal time to use the ROTO-VERT Casing Scraper is during the drilling out of cement, at which time it is run as a "follow-up" behind the bit. Thus in a single run you can also remove all hardened cement, mud, burrs and scale which might later damage swabs or testers, and cause packers or retainers to set prematurely—or never set at all.

EASY TO RUN—LOW-COST RENTAL

The Baker ROTO-VERT Casing Scraper is simple to run, and will effectively clean the inside of the casing *when either rotated or reciprocated* (vertical action). No service man is required, and the low rental cost is paid for many times over by freedom from future damage to bailers, swab rubbers and packers, as well as by the elimination of future delays and re-running expense.

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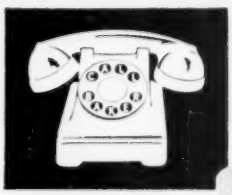

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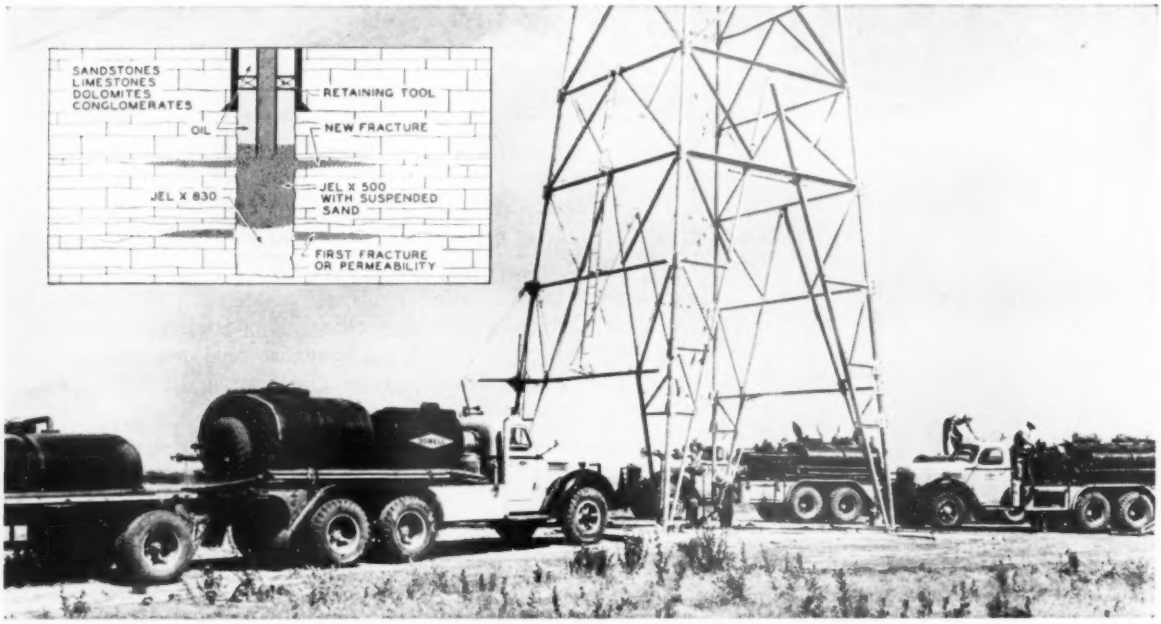
ROTOVERT

CASING SCRAPER

PRODUCT NO. 620-C

FIXAFRAC—TEMPORARY PLUGGING SERVICE—AIDS IN MULTIPLE FRACTURING TREATMENT

Production boosted from 2.3 to 65 BOPD; Fixafrac used to divert Stratafrac stages into different zones



Initial production from this well, after acidizing, was 50 barrels of oil per day. It declined over an 18-year period until production had fallen to 2.3 BOPD.

At this point, the operator decided to call in Dowell to determine how to increase production. Dowell's recommendation: a multiple fracturing treatment consisting of 1500 gallons of Stratafrac material and 300 gallons of Fixafrac material.

Dowell engineers performed the service, using Dowell trucks, equipment and fracturing materials. As a result of the treatment, the well swabbed 3½ barrels of oil per hour for 7 hours, after treating materials had been recovered. On pump, the well produced 65 BOPD.

Fixafrac is a temporary plugging service used between stages of Dowell fracturing and acidizing treatments to divert treating fluids into different sections. The material used in Fixafrac service, Jel X 830, carries suspended solids which react after treatment causing the material to liquefy and flow back freely to the well bore. No jel-breaker solution is needed following the treatment.

If you would like to know more about Fixafrac service, or any of the many other Dowell oilfield services, call the nearest Dowell office or write to Tulsa, Dept. D-15.

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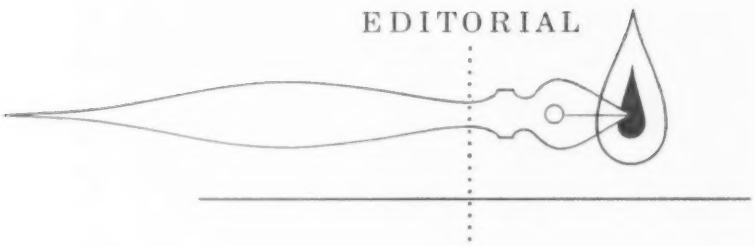


NEW FACE FOR JOURNAL OF PETROLEUM TECHNOLOGY

JOHN R. McMILLAN

CHAIRMAN
PETROLEUM BRANCH, AIME

With this issue, we are pleased to present a complete new design for our Petroleum Branch Publication. A design such as this has precise considerations involved in the same way as the design of a pumping unit, and it also has some intriguing problems that can only be solved by the rendition of expert opinion. We believe you as a member will be interested in these factors and how they were handled in achieving this new design for PETROLEUM TECHNOLOGY.

The primary considerations for the visual presentation of material in a magazine are:

1. The over-all appearance must be inviting and easy to read;
2. The typography and layout must appeal to the audience to which the publication is directed;
3. In the use of page space there must be a reasonable compromise between the presentation of maximum text matter and the arrangement of elements for readability and artistic effect;
4. The various elements, such as the types of editorial material, must be arranged so as to achieve their functional purpose, along with a pleasing balance.

In the past few years the Branch management has been aware of the fact that some of the above considerations could be improved in JOURNAL OF PETROLEUM TECHNOLOGY. Several months ago, the decision was made to proceed with such improvements, and a design artist of national reputation was retained to create a new design for the magazine. This designer was intimately familar with the purpose and scope of this magazine, and with the counsel of the branch staff proceeded to create a design that would achieve the desired result.

He worked on the following assumptions:

1. That petroleum engineers and men of science are on the whole conservative;
2. They read JOURNAL OF PETROLEUM TECHNOLOGY for increased knowledge of their field and not for entertainment;
3. They read the magazine more thoroughly and with greater intent than other types of publications.

He expressed his views as follows: "Our page must reflect an inviting, yet conservative atmosphere . . . the engineer will naturally respond favorably to anything that in his experience meshes properly, and to visual conditions that obey fundamental laws . . . he is annoyed, without knowing why, by irritating unbalance of layout, typography, and bad relationships of all kinds . . ."

These views determined the way in which the artist observed the primary design considerations enumerated above. To achieve an over-all inviting appearance he selected a new body type that is easier to read; he selected new type faces for headlines, bylines, and titles of papers; he removed some of the typographical elements formerly employed, and inserted pieces of art in various places to provide relief. A body type of minimum size for comfortable reading, and a narrower column width were chosen, along with layout factors to achieve the compromise expressed in consideration 3 above. Consideration 2 was also involved, in that the typography chosen is of a classical or conservative nature, rather than the modern or gothic type faces used for other purposes. The various kinds of editorial material that we believe will produce optimum results in a well-balanced magazine for the petroleum engineering profession were chosen and placed in a functional arrangement. The placement of advertising among these elements for maximum visibility was specified. Finally, a front cover treatment was selected that will endeavor each month to present something in the experience of the petroleum engineer that is technically accurate but in a pleasing artistic form.

Our purpose in creating this new design is to help the magazine do the best possible job in its particular field — the technical literature and professional functions of petroleum engineering. The Petroleum Branch is not a commercial publisher, and hence will not endeavor to publish such editorial matter as oil industry news, but will limit our pages to the material that properly falls within the scope of petroleum engineering. Our continuing objective in this will be to make the JOURNAL OF PETROLEUM TECHNOLOGY so good that the individual petroleum engineer will feel that he cannot afford to be without it. We believe this new design for its visual presentation will be a signficant step in this direction, and we believe you will like it. We invite you to write and express your views on it, either pro or con, for the most progress will come by proceeding on a solid foundation of membership opinion. ★★★

FEATURE ARTICLE

A CRYSTAL BALL for PETROLEUM ENGINEERS

FRANK M. PORTER

PRESIDENT
AMERICAN PETROLEUM INSTITUTE

"If our oil resources should develop a declining trend in the coming years, what would be the impact on the petroleum engineering profession?"

The possibilities suggested by this question are so numerous and encompass so many ramifications that I shall attempt only to indicate in the most general terms the developments which conceivably may arise in the years ahead of the profession.

Now, engineers by the nature of their calling are far-sighted men. This assemblage is as competent as any group in the world to demonstrate the improbability of any decline in petroleum reserves during our lives. It follows that any attempt to forecast the course of the petroleum engineering profession in a period of declining reserves necessarily involves a long, long look into the future and properly qualifies for my remarks the title, "A Crystal Ball for Petroleum Engineers."

In developing this theme, I have consulted no fortunetellers or soothsayers nor do I lay claim to any such powers for myself. It seems the soundest approach is to project the future from the past record. The oil industry today, and particularly the production phase, is largely the handiwork of the petroleum engineer, and his influence increases yearly. Indeed, the basic premise for our discussion here, declining reserves, is in growing measure conditioned by the ingenuity and professional competence of the engineer in recovering the maximum percentage of oil in place in known reservoirs, so that we can truthfully say the petroleum engineering profession to a marked degree holds its future in its own hands.

This article was written from the text of a speech given by Frank M. Porter before the Petroleum Branch Dinner at the AIME Annual Meeting in New York, Feb. 16, 1954.

History of Petroleum Engineering

The history of engineering in the petroleum industry remarkably parallels the story of the profession of engineering throughout the ages. Despite the fact that engineering is the oldest profession — for our early ancestors were building structures and designing tools long before they had invented money or a code of ethics — engineers have had to reestablish their status in each new country and in each new field of endeavor which has taken up engineering and industrial development.

So in the oil industry, like any other great industry dealing in a necessary commodity, oil has passed through many stages in its development. From the Drake well in 1859 on into the twentieth century, oil production was in the hands of the practical operators — men who had grown up in the oil fields and acquired their knowledge on the job. But as the industry grew, attracting more and more people, and more and more capital, the stress of competition put a premium upon better methods and equipment to produce more oil at lower cost. And thoughtful men early recognized the waste involved in rule-of-thumb production methods. Thus the industry's doors were opened to trained engineers.

It may be said that during the years from 1920 to 1935 petroleum production entered the "engineering era." Today, engineering sciences and techniques have been adopted in oil fields the world over, and the industry has arrived at the stage of its development where science, mechanics, equipment, and technically trained men prevail; where orderly development and production are keyed to the nation's welfare, in the best interests of the industry and its customers. Thus from our vantage point in the year 1954, we see that in some 30 short years petroleum engineering has grown from the most rudimentary beginnings into a highly technical and complex branch of engineering, worthy of its place with the other great disciplines of the profession. Now, from the same vantage point, let's look at the years ahead.

Future of Petroleum Engineering

In discussing the future of petroleum engineering in terms of petroleum reserves, two aspects of the subject demand exploration: The factors acting upon our reserves situation, and changing emphases in the oil industry and its engineering requirements.

Taking it as axiomatic that there will be petroleum engineers as long as there is any petroleum, I would like to elaborate upon a statement I made earlier, that petroleum engineers hold their future in their own hands to a considerable degree. In essence, the opportunities for and demands upon technical men in any industry can be measured by the number of problems to be solved. Taking this as a criterion, we can forecast abundant demands upon engineers in the field of oil production, for we are by no means anywhere near the point of having solved all our problems.

Drilling, production, and conservation or reservoir mechanics are the major areas in which the producing industry uses engineers.

Deep Well Problems

Our engineers and scientists have developed equipment capable of drilling below 20 thousand ft, but they have been unable to control the soaring ratio of drilling costs to depth of hole. As a result, very few wells are drilled below 15,000 ft. Even with all the modern improvements in drilling, we are still using a method containing many inefficiencies. Just think of the loss of energy involved in applying power to one end of thousands of feet of drill pipe in order to rotate a bit on the other end. Think of the work and time involved in hoisting up these thousands of feet of pipe in order to change the bit. On deep wells — say 15-20,000 ft — a single round trip may consume 10 or 12 hours. And, depending on rock conditions, one well may require a multitude of bit changes.

A lot of study is being devoted to this problem, both in the laboratories of individual companies and through cooperative research programs. The ultimate goal is an entirely new approch to the problem of drilling. Some progress has been made, with the result that equipment may be ready for field testing within the next few years. A great deal remains to be done. Our success in developing economically permissive methods of finding and producing deeper horizons than any we have found to date may defer indefinitely any decline in reserves.

Related to this problem, of course, is the matter of selecting drilling locations for these 4-mile wells. The geophysical methods now in use — the seismograph, magnetometer, and gravity meter — have been responsible for many of our major discoveries in the past 20 years. But all three are lacking in one vital respect — they do not guarantee that an oil reservoir does or does not lie under a given spot. There is plenty of room for research along this line.

Reservoir Problems

In production, we are working on ways to plug off unwanted water or gas sands without cutting off oil-bearing formations as well. Here again, progress has been made, most recently through the use of plastics. But most of the time our problem is one of opening up rather than closing formations, particularly at greater depths. The innovation of hydraulic fracturing methods has been a tremendous boon in opening up these tight sands, and has permitted recovery of much oil that would otherwise have been lost. But still, impermeability is a major obstacle to maximum recovery and we need still better methods of dealing with it.

As I mentioned, improvements in drilling equipment have enabled us to drill deeper holes in search of oil. But this deeper drilling has created a new set of problems in lifting oil to the surface. Hydraulic pumps and gas-lift systems have partially solved the problem of producing deep wells, but they aren't the whole answer.

Conservation and Secondary Recovery

All these problems are challenges to the petroleum engineer, and are important in extending the life of our known reserves. But over the long haul, the greatest hopes for maintaining our relative position with respect to our liquid oil deposits lie in the extensive research our industry is conducting on conservation practices and secondary recovery methods.

We are all too well aware of the wasteful production methods fostered by the law of capture during the rise of the oil industry. Today, we are doing considerably better, chiefly because conservation and secondary recovery techniques are applied early in the life of a field with consequent improvement in recovery efficiencies. For these improvements the industry is indebted to the petroleum engineers. They have shown us the value of well spacing and the use of maximum efficient production rates. They have led the movement toward cooperation between the industry and the governments of the oil-producing states in establishing unitization laws and other conservation measures, and in the utilization of the forum provided by meetings of the Interstate Oil Compact Commission.

Through research and the practical application of research in secondary recovery operations, reservoir engineers are providing us with the most certain source of additional reserves. Modern secondary recovery techniques, coupled with favorable market conditions during the past decade, have enabled us to bring new life to many old fields in which primary production had declined to a low level. Today, a great deal of research effort is being directed toward developing even better methods for secondary recovery. This research effort is along two general lines of investigation.

The first is directed toward improving the present techniques of gas repressuring and waterflooding to maintain reservoir energy. A new approach to repressuring is high pressure gas drive, which is currently being field tested. In waterflooding, extensive research is being carried out on various wetting agents, additives which improve the displacement efficiency of water, and help to prevent encroachment.

The other line of secondary recovery investigation is directed toward the development of new types of reservoir energy. One is the method called "miscible fluid flooding." There have been other ideas advanced at different times, some exhibiting considerable imagination, such as the "microbe theory" which was publicized some years ago. This idea involved seeding the formation with bacteria which would multiply and force the oil molecules out of the pore spaces in the rock and into the waiting oil wells. The process would have entailed practically no expense, and in fact had only one defect — it didn't work.

Underground Combustion

Perhaps the most promising new technique is that of underground combustion which is now being tested in the field by two or three companies. Theoretically, this process can achieve 100 per cent displacement of the oil, though from 5 to 15 per cent of the reservoir oil will be lost through combustion. A great deal is at stake in these research projects, since a few percentage points in recovery efficiency over our present average could well be the equivalent of adding to our proved reserves another field even as large as East Texas and without the attendant costs of exploration and development.

Those, very briefly, are some of the major areas which challenge the petroleum engineer today, though they by no means represent the complete list of problems. They involve billions of dollars of revenue to the industry, and more important, billions of barrels of what I believe to be our most precious natural resource. That is why I say that petroleum engineers hold their future in their own hands. Their success in solving these problems will determine their tenure in the industry — and will determine the course of the industry itself.

The Unavoidable Decline

Nevertheless, you may contend that all these arguments are begging the question — that no matter how distant the date, some day we must inevitably and unavoidably enter upon the phase of declining reserves of oil. So far the industry has been, and will be for the foreseeable future, a real-life illustration of the mythical Cornucopia — the horn of plenty — which could never be emptied, no matter how much was poured from it. But oil is no myth. The day is bound to come when we will begin to use more oil than we can replace. That may be several generations away, but there are some who even now believe that we can demonstrate mathematically the finite limits of the total quantity of natural crude petroleum that we can hope to recover. As that time begins to make itself known, synthetic fuels programs will increase in intensity and undoubtedly fill the gap between anticipated demand and supply. The industry has every confidence, of course, in its ability to do this. The known factors with respect to synthetic fuels and the necessary raw materials — coal and shale, constitute one of the strongest rebuttals of prophecies of an oil shortage.

Synthetic Fuels

It is entirely conceivable, however, that long before we actually need to resort to the extraction of oils from coal and shale, other and newer sources of power will have made the need superfluous. I do not intend for this remark to give anyone the idea that I think we should abandon the synthetic fuels program — quite the contrary. It would be most unwise were the industry to postpone the development of synthetic fuels until the need arises even if competition would let us do so. If anything, we should step-up our research into synthetics. What I am referring to is the possibility that developments outside of our industry may affect our market for home-heating fuels and also commercial heating. Periodically we hear of experimental work on solar furnaces as a source of heating energy. This is a field about which I know nothing, but I do know that research men work wonders and it may well be that they will find a way to reduce the solar furnace to useable size and to keep it working on cloudy days and cold winter nights.

Atomic Energy

Atomic energy has, of course, become a very much discussed subject, and who can say that way down in the future some other new completely unheard or unthought of medium might not also interfere with the heating-oil portion of our present demand. The cost of these newer mediums will, of course, affect the rate by which our fuel market might be reduced. However, it seems pretty well agreed, even at this time, that atomic energy will probably never replace liquid fuel in the propulsion of our many automobiles and transport units of that type.

A considerable amount of basic research in commercial uses of atomic energy apparently has already been done. It may be that widespread use of the atom in industry is nearer than we know. The English have already stated publicly than in 10 or 20 years all their energy requirements will be exerted from the atom. Certainly I cannot argue with this prediction although I see certain problems involved in such rapid obsolescence of capital investments in equipment powered by our present fuels.

Petrochemical Business

As you well know, the oil industry is even now doing a very considerable business in petrochemicals, and is supplying approximately one-half of the basic raw material which other units in the chemical industry convert to marketable products. The percentage this represents of our total crude oil use still remains very small. Yet the relative growth of the petrochemical industry in recent years has been nothing less than amazing.

A couple of years ago we were saying that over 1,200 products were made from petroleum. I do not know whether anyone has made a more recent count.

but I suspect that figure has increased sizeably since then. It is believed that about 2,500 different chemicals can be extracted from oil and gas. It has been estimated that one and a half million different compounds may be obtained if commercial uses can be found for them. You can see that we are just beginning our research into potential uses of petroleum. It can, therefore, be said that certain future development may greatly change the nature of the demand for the products of petroleum.

Since its earliest beginning our industry has been a dynamic changing enterprise. The shape of things to come portends even greater change in the years ahead. We are going to be busier than ever trying to keep up with ourselves. The day has passed when any business, especially the oil business, can be made to conform to a fixed pattern. Research in any business or industry is the fact-finding agent of scientific and common sense management. It offers protection against obsolescence and it is as much a part of a sound business program as accurate intelligence is in military planning.

A Prophesy

I prophesy that with our abundant reserves and the large number of untested areas known to be favorable to the accumulation of natural petroleum, and our knowledge of the ability to synthesize cost and to extract oil from shale, petroleum will be available and will continue to play a major part in supplying this country with ever-increasing portions of its energy requirements. But granting that solar heating and atomic power do arrive on the scene more prominently, and are available at a cost that is relatively more attractive than petroleum fuels, I foresee no need for the petroleum engineer to become disturbed. And further, since he is of necessity a "Jack-of-Many-Trades" in an engineering sense, what industry would be better equipped to move into these new spheres of fuel supply than this far-seeing petroleum industry that we are all a part of. Our industry has attained leadership in energy-fuel supply, and unless I miss my guess by a very wide margin, it intends to retain that leadership.

Since the petroleum engineer borrows his skills and techniques from all fields of the profession — mining, civil, mechanical, chemical, electrical, and all the rest, he is in a position to change his stripes as the occasion requires, but whatever his engineering branch may be, he lives up to the words of a famous English engineer of 150 years ago when he defined the engineering profession as "The art of using forces and materials of nature for the use and convenience of man" — to which I would like to add "however he may be called upon to do so." Therein, I believe, lies the answer to the future of petroleum engineering and indeed to any branch of engineering.

If it is true, as I have said at the beginning of these remarks, that the industry today is in large measure the handiwork of the engineer, it is no less true that the petroleum engineer is a product of our industry, and, being the basically well-founded individual he is in broad engineering science, his functions and responsibilities will change within its structure as the industry changes. So, if, as, and when the petroleum industry should lose part of its fuel market to other sources of energy more attractive to consumers, and the industry moves further down the road to diversification of products, and if petrochemicals do become more important in the picture, which transformation some individuals already believe has begun, the petroleum engineer will go along with, and as part of that transformation.

About the time the first petroleum engineers were beginning to show up, the carriage industry was invaded by a new arrival — the automobile. It wasn't too long after that that the buggy designer and the blacksmith were becoming automobile body stylists and tool-and-die makers.

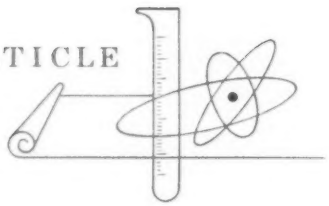
Now there are a great many automotive engineers and automotive mechanics. Some of them can still remember the days back yonder when they were putting the fringe on surreys or retreading horses' hooves. Yes, their titles and functions have changed but basically they are serving the carriage trade — which has itself grown to include over 75 per cent of American families.

Summary

I find, in summary, that I cannot answer the posed question except on hypothetical grounds. As a hypothesis, a declining trend in the reserves of natural crude petroleum would, I imagine, result in declining opportunities for petroleum engineers after they had exhausted, with their friends the geologists, all possibilities of halting that trend. But then would come the synthesis of coal and the extraction of oil from shale and oil sands, and probably an expanding need for general engineering knowledge. Practically, however, I honestly cannot envision declining opportunities for petroleum engineers because I do not think anything like that will ever occur as long as there is a need for petroleum.

Change and time alter all things, just as it has, and is still altering, the character of the petroleum industry, and just as it has altered the character of all of man's institutions. Just so will this same process of change at some distant date alter the functions and perhaps the titles of what we now call petroleum engineers. This process of change and development is the challenge of competition in a free economy. In it is the hope, but never the threat, of the future. ***

FEATURE ARTICLE



TRENDS in DRILLABLE ACREAGE

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MEMBER AIME

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Introduction

The fact that proved crude-oil reserves, as reported by the American Petroleum Institute, have shown a steady increase is completely satisfying to some as regards future supplies. Some look into the situation a little deeper and conclude that because years' supply, or the ratio of reserves to demand, has not shown much change in the last 15 years that there is no cause for concern. Both groups disregard, or are ignorant of the fact, that the reserves of 10-15 years ago were estimated on an extremely conservative basis, as evidenced by the billions of barrels in "revisions" that have been added to reserves in the last eight years.* These revisions do represent reserves to be produced in the future, but the majority of them are not real discoveries and, in general, have little relationship to drilling, past and future.

Some drilling superintendents are considerably worried as to where to locate future development wells. They are more interested in acres than in barrels of reserves, which focusses attention on the fact that the time has arrived to look into acreage reserves as well as oil reserves. Perhaps acreage has become, or will soon become, more of a limiting factor on drilling than reserves and all the other factors of price, steel, etc., put together.

As with all segments of the industry, except possibly distribution, the statistics bearing on drillable territory do not measure up to the over-all importance of petroleum. Fortunately, the Petroleum Branch of the American Institute of Mining and Metallurgical Engineers has preserved and improved its annual data on wells and acreages by pools, and the American Association of Petroleum Geologists has compiled valuable information on the results of exploratory drilling.

Evaluation of the data available and the labor involved led to a decision to examine the relationship of reserves to drilling for two states, California and Pennsylvania, and for the United States as a whole, and to analyze the acreage data for Arkansas.

*API reserves start with Jan. 1, 1937; API revisions began in 1945. This article is an independent study and does not necessarily reflect the viewpoint of the Office of Defense Mobilization.

Reserves versus Wells

The reserve data (API) for the two selected states and the United States are as follows in millions of barrels:

	United States	California	Pennsylvania
Jan. 1, 1946	19,942	3,318	111
Jan. 1, 1952	27,468	3,761	95
Jan. 1, 1953	27,961	3,854	122

In the seven-year interval, reserves in California have increased 16 per cent, in Pennsylvania 10 per cent, and in the United States 40 per cent. The largest increase, that for the United States, does not indicate a falling off in places to drill until it realized that it is considerably less than the gain in the drilling rate. Furthermore, a large part of the increase in reserves has come from revisions of previous estimates, which on a net basis, add comparatively little to drillable acreage. The API does not publish the figures on revisions by states, but these data for California are available and it can be assumed that "extensions and revisions" for Pennsylvania are all revisions. The breakdown for these two states and the United States for the six years 1946-1951 is as follows in millions of barrels:

TABLE 1 — BREAKDOWN OF STATISTICS OF 1946-1951

	U. S.	California	Penn.
Total reserves "discovered"	19,199	2,446	58
By new fields and pools	2,929	269	
By extensions	9,146	663	
By revisions	7,124	1,514	58
Production	11,675	2,004	73
Net increase in reserves	7,524	442	− 15
Net increase in "reserves" without revisions	400	− 1,072	− 73

"Nibbling"

Had it not been for the reserves added by revisions, production could not have been met by a large margin in California, not at all in Pennsylvania, and only by a small margin in the United States. This illustrates how important the revisions have been in recent years. Although many of the revisions reflect larger estimates for acreage and for per acre recovery, some are the result of what has been referred to as "nibbling." Nibbling refers to the practice of stepping out a location or two, but not far enough so that resultant discoveries are classed as extensions.

On the other hand, revisions made to reflect recovery technology and higher prices might increase the number of drilling locations. Thus upward revisions in a stripper state like Pennsylvania probably reflect the spread of secondary recovery, which generally means the re-drilling of wells. All the revisions related to technology and economics are not positive ones, for example, recent evaluations of costs in the Spraberry, Tex., field have resulted in a downward revision in reserves and a large decline in the number of wells contemplated.

There is another class of revisions that could result in an increase in drilling locations. That is revisions made to include the reserves of producing formations, usually shallower, that were passed up in the initial development. This oil was not listed as "discovery" when first drilled through, but now that it is being produced it must be included in the reserves as a revision. Such revisions are important at this time in Kansas, Oklahoma, and Texas, where drilling of shallower formations has been a major factor in raising total U. S. completions to new heights, and in reversing the trends for average depth and ratio of dry holes.

Reserve Per New Producing Well

The reserve per new producing well for the United States is now known, but generally speaking it must be at least 100,000 bbls to yield a profit. Dividing this into the total new reserve of 12,075,000,000 bbls, that was found in the six years (see table above), gives 120,750 as a rough measure of the number of new wells that could be drilled in the new territory. However, about 211,000 wells, exclusive of gas wells, were actually drilled in the United States in the six-year period. The difference of about 90,000 wells includes many thousands of dry exploratory wells drilled outside of established reserves, and thousands drilled on the edges of established pools, but the major portion represents wells drilled in the older fields under closer spacing.

A similar analysis for California and Pennsylvania shows relatively worse situations.

	Total Reserves (Bbl)	
	Calif.	Penn.
Jan. 1, 1946	3,318,000,000	111,000,000
Jan. 1, 1952	3,761,000,000	95,000,000

Producing Wells		Reserves per Well (Bbl)	
Calif.	Penn.	Calif.	Penn.
23,180	83,200	143,000	1,300
29,630	78,800	127,000	1,200

For California, the average reserve per well of 135,000 bbls, divided into the total new reserve of 932,000,000 bbls, gives about 6,900 new locations; however, there were 13,149 wells, exclusive of gas wells, drilled in the six-year period.

In Pennsylvania there were virtually no new reserves discovered, hence few primary locations were added. In the six-year period there were nearly 7,500 oil wells completed in Pennsylvania, most of them producers under the five-spot method of secondary recovery. The expansion of secondary recovery continually provides a new quota of drilling locations, but the overall number is limited by depths and other factors and the quality is second-rate.

The average reserve per producing well for Pennsylvania of about 1,250 bbls is worthy of comment because of its small size and because of its relationship to continued revisions in reserves. Assuming that these stripper wells continue to be operated, the average future production should total at least three times that figure. If so, the cumulative revisions for the future in Pennsylvania would total about 200,000,000 bbls or double present reserves.

Acreage versus Wells

The other basis for measuring the trend in number of drilling locations is in terms of acreage. This should yield a better answer than the reserves method as there is a direct relationship between acreage and drilling.

The acreage available for drilling may, for the purpose of logical presentation, be divided into the following classes:

1. Inside acreage
2. New fields and pools
3. Extensions
4. Formations initially passed up
5. Secondary recovery

Inside Acreage

There is considerable undrilled acreage within many of the older fields of this country but the extent is unknown. Even though it were possible to count this acreage, it would not be valid to translate the total into future wells by using an average spacing factor, as the rise in development costs has made most inside drilling uneconomic. The demand for crude oil in the last 10 years, particularly the demand during World War II, smoked out considerable of the best inside acreage, including considerable fee acreage in California. As regards the remainder, the longer the existing wells are allowed to drain some of the oil from under the inside locations the less likely that these inside locations will ever be drilled. The fact that it would "take a thousand years to fully exhaust some fields" with the existing widely-spaced wells, does not mean that many of the inside locations are being held in reserve. Several conditions, mostly economic in nature, have to be favorable before an inside location is drilled, meanwhile, rising costs and competition of other sources continually make it more unlikely that it will ever be drilled.

National Acreage Data

Although statistics on inside acreage are generally unavailable, it was decided to look into the national acreage data to a limited extent.

Forty of the largest fields discovered in 1936 had a total of 883 completions in 1941 as compared with 123 completions in 1946 and 90 in 1951. The total completions for the group as of the end of 1941 and 1951 were 8,732 and 10,273, respectively. The trend of these data indicate that the ultimate number of primary completions for this group of fields will be about 10,750 and that beginning Jan. 1, 1954, there will be only about 325 locations that will be drilled in the future, say in the next 13 years to 1966. Although drilling for the group was extended over a long period of time (30 years), 81 per cent of the wells were completed in the first four to five years. This would not indicate any tendency to hold back development, that is, to put inside acreage in mothballs.

Forty leading fields discovered in 1946 had 343 completions during 1951, compared with 883 completions in 1941 for the 40 fields discovered in 1936. Further-

more, the 1946 group had a cumulative total of 2,774 completions in the first five years, compared with 8,732 completions for the 1936 group. The striking contrast in these figures merits further consideration.

A Comparison

Every oil field is different and it would not be proper to compare one discovery in 1936 with one discovery in 1946. However, there is a general comparability for groups of 40 fields, particularly when each group contains virtually all of the largest discoveries in the year selected. Therefore, the fact that the 1946 group, when compared with the 1936 group, had only 39 per cent as many completions in the fifth year, and 32 per cent as many completions in total at the end of the fifth year can be taken as proof of what has been generally evident for some time, namely, that the newer discoveries are smaller and the wells are wider spaced. To confirm these general conclusions the spacing data for the two groups were studied with the following results:

	40 1936 Discoveries	40 1946 Discoveries
Acres, end of 1941	143,225	
Acres, end of 1951		81,705
Completions, end of 1941	8,732	
Completions, end of 1951	—	2,774
Acres per well	16	29

The principal conclusion that can be drawn from the above is that whereas thousands of drillable inside locations still remain, they are mostly to be found in the fields more than 25 years old. The new acreage added to the reserve has been getting smaller each year, making it necessary to exhaust the inside locations of the older fields at an increasing rate.

New Fields and Pools

The acreage of new fields represents the virgin, hence the preferred type of addition to drillable territory. The acreage of new pools is a less preferred type as it is rare that drilling in a new pool is as dense as it was in the initially discovered pool of the same field. This is due partly to dual completions, but mainly to the fact that the best pools are generally found first and are generally shallower in depth.

Most new fields and pools are found close to refineries and pipe lines, but some, like those in the Williston Basin, are on the frontiers. As far as drilling is concerned, the only differences are that the wells on the frontiers are wider spaced and are completed at a slower pace.

Extensions

An extension is a lateral discovery which adds acreage but not drilling sites in the same proportion. This is because extensions are generally made on the flanks of the main structure where the reserves per acre are below the average. Also, edge wells are generally deeper and more expensive, hence are wider spaced.

Formations Initially Passed Up

During the intensive development of the last 30 years many pools were passed up in the search for the bonanza. As many of these pools were relatively close together and of the same gelogical age, it could be said that the whole formations over wide areas were passed up.

In recent years the necessity of finding new reserves has made these areas more attractive for drilling, particularly in Kansas, Oklahoma, and North Texas, where the stratigraphy is favorable. Drilling in these passed up areas, where the formations are generally shallower, is believed to be playing an important part in current drilling trends, such as a record number of completions, a decline in the average depth of completions, and a decline in the percentage of dry holes. Both of these declines reversed trends that had prevailed for several years.

The increases in the price of crude oil starting early in 1953, plus continued technological improvement, have spurred the development of passed up areas though it is doubtful if these wells are as profitable today as they would have been 25 years ago. In any event, a considerable acreage has been thrown open for drilling. It should be borne in mind, however, that these wells will be second-rate wells and that acreage available for this type of scavenger operation exists only in a small number of states.

Secondary Recovery

Secondary recovery is another type of scavenger operation, different from that described above only in that the production is not primary. Where present wells are in poor condition or poorly spaced, it is necessary to drill new wells for injection and production.

Potentially, secondary recovery opens up a vast area for the drilling of shallow wells of 1,000 to 3,000 ft in depth. However, the wells are third rate with a low margin of profit. Increased cost and competition with other sources of oil could keep this type of drilling from increasing much beyond the present level of several thousand wells annually.

The best way of measuring the trend of drillable locations should be the direct method, that is, a comparison of the acreage added by discovery with the acreage used up in drilling. However, with 5,000 to 10,000 oil fields to consider and the acreage statistics lacking on many of them, the problem on a national basis would be most formidable. Fortunately, the AIME has compiled annual data by fields and pools for most of the states. Of these states, Arkansas was selected as the test case to measure new acreage versus drilling in the years since the war. The pertinent data developed for Arkansas for the period 1945-52 are as indicated in Table 2.

As indicated in line 7 of the table, there appears to be a recent decline in the annual number of surface acres added. On the other hand, the number of wells drilled has generally increased, hence the surface spacing factor (line 3) declined from 14.5 acres on Jan. 1, 1950, to 13.9 acres on Jan. 1, 1952.

Subsurface Acreage in Minor Pools

The discovery of what might be termed subsurface acreage in minor pools appears to have increased in Arkansas in recent years. Subsurface acres represent the acres in minor pools that generally lie below the major pool on which the surface acreage of the field was based. However, these pools are smaller and generally deeper, hence the well spacing is much wider — about twice as wide — for profitable operations. In other words, the discovery of numerous deep pools in the Cotton Valley and Smackover formations in Arkansas adds relatively little to drillable acreage. This is particularly true of that part of the Smackover formation known as the Reynolds zone, which produces gas or condensate in most fields.

TABLE 2 — NEW ACREAGE VERSUS DRILLING DURING 1946-1952 PERIOD IN ARKANSAS

	1946	1947	1948	1949	1950	1951	1952
1. Surface acres first of year	101,756	104,045	107,717	111,730	115,535	116,150	117,797
2. Cumulative oil wells drilled to first of year	7,342	7,460	7,653	7,804	7,983	8,245	8,491
3. Surface spacing on first of year (acres)	13.9	13.9	14.1	14.3	14.5	14.1	13.9
4. Oil wells drilled during year	118	193	151	179	262	246	220
5. Surface acres added during year from new fields	240	160	920	320	605	480	*
6. Surface acres added during year from pool extensions	2,049	3,512	3,093	3,485	10	1,167	*
7. Total surface acres added	2,289	3,672	4,013	3,805	615	1,647	*
8. Subsurface acres added during year from discovery of new pools	520	380	100	690	920	2,220	*
9. Subsurface acres added during year by extensions of minor pools	404	1,694	880	267	565	378	*
10. Total subsurface acreage added**	924	2,074	980	957	1,485	2,598	*

* Not available.
**Exclusive of extensions in primary pools included in line 6.

Of all the producing states west of the Appalachians, Arkansas appears to be the most hemmed in as regards exploration. Wildcatting cannot spread east, south, and west because of state boundaries, and, a radical change in geology in the center of the state makes oil occurrence in the northern half of the state virtually impossible. Deeper exploration has been fairly successful in recent years but the base of the favorable sedimentaries appears to have been reached in most fields. This basement is only in the Jurassic, a comparatively young formation, but the Palezoic geology below is complex and, even if solved by drilling, would probably yield nothing but small gas fields.

Arkansas is living off its fat as far as drilling is concerned and only has several thousand drillable locations left. Spurts in drilling, as in 1953, will speed the eventual decline in drilling.

So far the discussion has been confined to development drilling. Exploratory drilling in Arkansas, which has amounted to about 30 per cent of all drilling in recent years, will probably show an even faster decline, as the geology of the state leaves little room for continued expansion.

California Situation

It was the original intention to make the same study of acreages in California as was done for Arkansas. This idea was abandoned both because of lack of data and the size of the job. However, some information was prepared for California without too much difficulty by segregating 30-odd large fields which have close to 80 per cent of the reserves.

As of Dec. 31, 1951, this group of large fields had a total surface area of 247,000 acres and nearly 25,000 producing oil wells. This indicates a spacing of about one well for every 10 acres; however, indications are that total completions in this group of fields totaled about 35,000, or a spacing of 7 acres per well. However, these spacing factors are poor indicators as to undrilled locations as they give no consideration to the subsurface acreages of underlying pools.

Drilling in the group has been declining slowly; in 1951 there were 1,023 completions compared with 1,207 in 1947. Total reserves of the state on Dec. 31, 1951, were 3,761,000,000 bbls, of which 80 per cent for the group amounts to 3,009,000,000 bbls. Thus each average new well drilling in the large fields on that date was headed for 86,000 bbls of crude-oil reserves. This average does not appear large enough to support much drilling until it is realized that these fields are comparatively shallow, the dry-hole ratio is low, and the reserves will be revised upward by continued revisions.

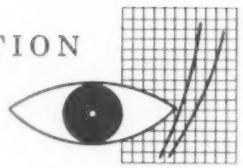
Conclusions

Although Arkansas with its restricted territory cannot be called a typical state, it is at least indicative of what must eventually happen to drilling in all states.

Spurts in drilling in the United States, such as have occurred since the middle of 1953, will probably occur again from time to time, but they only serve to speed the eventual decline. It is not possible to predict the peak of drilling as that depends on two unknowns, discovery and inducement. Since the work on this paper was started, data on drilling in 1953 have become available. According to the AIME statistics, there were in excess of 49,000 wells completed in 1953, as compared with the expansion goal of 55,000 wells, sponsored by the Petroleum Administration for Defense. Over the last three months completions have averaged just over 1,000 per week. Such a rate put 55,000 wells within the range of probability, but is considerably below the 65,000-well level, tentatively proposed for 1955.

Sufficient steel and a satisfactory price have been considered as the chief determinants for drilling. Steel is not a problem except in emergencies. A crude price rise would increase the number of drillable locations but too much of an advance would stimulate competing sources of oil, imports and synthetics. In the meantime a physical factor, acreage, may prove to be more controlling as regards the trend in drilling than the economic factors. ★★★

REPORT and INTERPRETATION



JOE B. ALFORD

EXECUTIVE SECRETARY
PETROLEUM BRANCH, AIME

With this issue we inaugurate a column to be published monthly in JOURNAL OF PETROLEUM TECHNOLOGY *under the above heading. It will be patterned somewhat after "The Drift of Things," a column formerly written for AIME magazines by Edward H. Robie, Secretary of the Institute, and it will also replace the column we have written during the past year or so titled "Petroleum Branch Affairs."*

We have no illusions about doing as good a job with this column as Secretary Robie did with the "Drift." His column was one of the most popular features of Institute magazines, and it has been missed by members since the press of other work forced him to discontinue it about two years ago. The primary purpose of the monthy "Report" will be much the same however, in that we will endeavor to report on topics of interest within the Institute, the Branch, and the profession, and to give these topics some interpretation when such is called for. Ours will not be an "ivory-tower" essay on the chosen subject, but more of a factual analysis of it, with the expression of a conclusion when appropriate. We will normally write the "Report" but on occasion will invite other members of the staff and the Institute to contribute a column. Our entire purpose is to inform the membership on matters of interest. We will welcome your suggestions on subjects that you would like to see covered here. We believe that this monthly report is needed, and will endeavor to make it something of value to you.

Publishing a Balanced Magazine

At various times we have been asked by members why it is necessary to publish so much material of a highly technical nature in JOURNAL OF PETROLEUM TECHNOLOGY — why not make it more practical. At other times, other members have asked why it is necessary to publish such things as an editorial and general reviews — why not leave such material out and use the space for good technical papers on reservoir engineering.

We do not wish to imply criticism of either view. Each has its place. But the fact that such diametrically opposed views are held by members of the Branch necessitates a publishing program that will give something to both, as well as the additional viewpoints in between.

These considerations were the basis for selecting the elements that we believe will constitute a balanced magazine for the entire membership. The elements are arranged in a functional order in the new design for PETROLEUM TECHNOLOGY launched with this issue, and this template will be followed in future issues.

As John R. McMillan stated in his editorial in this issue, we will endeavor to do the best job we can with the technical literature and professional functions of petroleum engineering, and will limit our pages to material within these fields. For instance, we do not have the staff or the space to cover oil industry news so we will not publish a news page or department. The editorial material which we will publish each month is as follows:

Editorial: A single page will present an editorial written by an outstanding person in industry, an AIME member, officers of the Branch, or Institute staff members. These editorials will express the opinions of the writers, and will have no official endorsement as such from the Branch. Their purpose will be to present different points of view on topics of interest in order to stimulate thought and discussion. The page will be open to any member who wishes to express himself.

Feature Articles and Technical Notes: Eight to ten pages will be devoted to editorial material in these two forms. The feature articles will be of more general interest and a more practical nature than the customary transactions paper. The technical notes will be short presentations of technical material that is newsworthy or unique. This material will be selected by the General Editorial Committee of the Branch.

Report and Interpretation: Explained above.

Transactions: The fundamental purpose of the magazine is to distribute to the membership the permanent literature of the profession in the form called *Transactions*. Hence, this section will comprise about 30 pages in each issue, with the papers appearing in it being selected by the Transactions Editorial Committee of the Branch. The type from which this section is printed is kept standing, and currently an additional 5,000 copies of this section is printed from it for the annual *Transactions* volume.

Meet the Authors: A new feature to give proper recognition to those members who write the literature of the profession.

Branch and Institute Affairs: Several pages will carry news of the Institute, the Branch, Local Sections, individual members, and news briefs of professional interest. In addition, this section will publish those proposed for membership, and employment notices.

Advertising will be placed in between these various sections to achieve maximum visibility to the advertiser, and to provide ease of reading. Advertising has its editorial nature, and will be of interest to most readers.

Although this publishing program is not completely of an omnibus nature, we believe it will provide something of interest to everyone engaged in petroleum engineering. We believe this is necessary if the profession is to achieve its maximum potential development on a long range basis. ★★★

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PETROLEUM TRANSACTIONS

OIL PRODUCTION after BREAKTHROUGH — as INFLUENCED by MOBILITY RATIO

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ABSTRACT

The study of the influence of fluid mobilities on the sweepout pattern resulting from the injection of gas or water has been extended to cover the production period which follows breakthrough of the injected material. Mobility ratios over the range common in field operations (0.1 to 17) were studied for several pattern floods (five-spot, staggered, and direct line drive). The experimental data required for these studies were obtained by the use of the x-ray shadowgraph technique using miscible oil phases of different viscosities in porous plate models of a reservoir element. From the shadowgraph pictures obtained before and after breakthrough of the injected fluid, flowing ratios at the producing well and cumulative volumes injected were calculated.

The method for applying such data in predicting field behavior is illustrated for a water flood of a five-spot. For this case a range of mobility ratios of 0.5 to 5.0 results in: (1) nearly complete (95 to 100 per cent) sweepout pattern efficiencies at abandonment conditions, (2) production after breakthrough being responsible for as much as one-third of the total recovery at the lower mobility ratios, and (3) a twofold variation in the operating life of the reservoir.

[1]References given at end of paper.

Manuscript received in the Petroleum Branch office July 31, 1953. Paper presented at the Petroleum Branch Fall Meeting at Dallas, Tex., Oct. 19-21, 1953.

Discussion of this and all following technical papers is invited. Discussion in writing (3 copies) may be sent to the offices of the Journal of Petroleum Technology. Any discussion offered after Dec. 31, 1954, should be in the form of a new paper.

INTRODUCTION

In determining the merits of a secondary recovery operation, the fraction of the reservoir which is ultimately to be swept by the injected fluid is of major importance. Because of its significance a large amount of research has been applied to the study of areal sweepout efficiency. Muskat, Wyckoff and Botset[1,2] have presented the classic analysis of the pattern efficiency at breakthrough for several injection patterns in which the mobility of the fluids ahead of the injected phase front was equal to the mobility of the fluids behind the front. Aronofsky[3] has extended this analysis of recovery at breakthrough through numerical computations and by the stepwise use of the potentiometric model to include the effect of different fluid mobilities ahead of and behind the invasion front on the line drive performance. Fay and Prats[4] have also employed numerical computations to show the influence of one other condition of fluid mobilities on the five spot flood.

In a previous paper[5] a new method of attack on this problem which employed x-ray and porous plates was described. At that time experimental results were also presented which described the effect of fluid mobilities on the reservoir area contacted by the injected fluid at breakthrough for the five spot and direct line drive patterns.

Most of the literature pertaining to sweepout pattern efficiency has emphasized the pattern which is obtained at breakthrough of the injected phase. The increase in the sweepout pattern which occurs after breakthrough

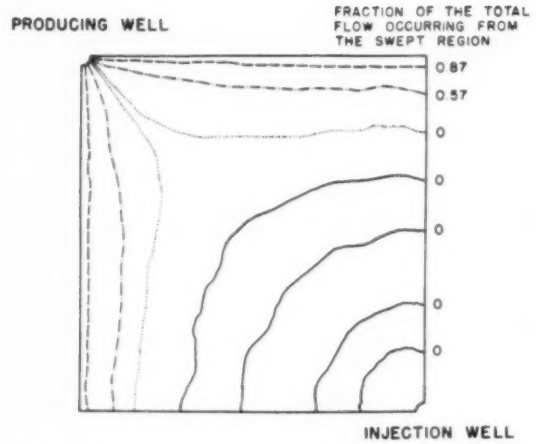

FIG. 1 — SWEEPOUT PATTERNS AT SUCCESSIVE TIMES DURING FLOOD OF A FIVE SPOT PATTERN AT MOBILITY RATIO OF 1.06.

and during the period of production of both displaced and displacing phase has been given little attention. Hurst[6] presented an analysis of production after breakthrough in a five spot flood for a limited case in which the mobility of the fluids in the swept and unswept regions were equal. Fay and Prats[4] added the recovery after breakthrough for the case in which the mobility of the fluids in the unswept region was one-fourth that in the swept region.

Because of the limited data available on the phase of production history after breakthrough and the emphasis which most of the literature has placed on recovery at breakthrough, the fraction of the reservoir considered in engineering studies for injection operations has perhaps often been taken as that reported for first breakthrough. To define accurately the economics of a flood and to make the proper choice of injection pattern to be employed, the reservoir engineer needs data concerning both the sweepout pattern at breakthrough and the continual enlargement of the pattern which occurs in the period of production following breakthrough. The development of the x-ray method provides the tool for studying the performance in both periods of production. This paper presents the results obtained by this method in studying the production performance before and after breakthrough for the five spot, staggered line drive, and direct line drive to cover the wide range of fluid mobilities generally encountered in field operations.

For floods in which no saturation gradient is present in the mobility of the fluids in either the swept or unswept region, the mobility ratio (M) of the system can be characterized by the ratio of the sum of the mobility of each phase flowing in the unswept region ahead of the front to the sum of the mobility of each phase flowing in the swept region behind the front.[5,9,10]

The mobility of a phase is expressed as its relative permeability divided by its viscosity. The mobility ratio can then be written as shown below.

$$M = \frac{\left(\frac{k_{r1}}{\mu_1} + \frac{k_{r2}}{\mu_2} \ldots\right)_{\text{unswept}}}{\left(\frac{k_{r1}}{\mu_1} + \frac{k_{r2}}{\mu_2} \ldots\right)_{\text{swept}}}$$

k_r = relative permeability
μ = viscosity, centipoise
numerical subscripts denote flowing phase 1, flowing phase 2, etc.

EXPERIMENTAL PROCEDURE

The use of the x-ray shadowgraph technique to study the recovery of oil resulting from the increase in the area contacted after the initial breakthrough of the invading phase consists of taking radiographs (x-ray pictures) of a porous model during a simulated flood employing the desired fluid mobilities. Since the injected fluid is rendered more strongly absorbent to x-rays than the reservoir fluid, most of the x-radiation passing through the swept portion of the model is absorbed and thus does not strike the x-ray film. On the other hand the x-radiation passes readily through the remainder of the model to strike and expose the film. Thus each radiograph taken during a flooding operation clearly shows the area which has been contacted by injected fluid at that time.

A Westinghouse medical x-ray unit having a maximum working potential of 80 kilovolts was used in these studies. A Fairchild x-ray roll film cassette with a sequence control was used in conjunction with the x-ray unit. This combination permits completely automatic operation, taking radiographs at predetermined intervals and recording the time at which each radiograph was exposed.

The models used for these experiments were cut from ¼-in. thick alundum plates. The surfaces were sealed with a ceramic type glaze. Fittings were fixed to the wells with a plastic adhesive. For all of the model results to be discussed here the injected and displaced phases were miscible in all proportions. Miscible fluids were used in obtaining a good control of the mobility ratio for a given experiment. This was possible since the displacement efficiency behind the invading front was near 100 per cent. The experimental results illustrated in Fig. 2 show a 98 per cent displacement efficiency behind the invading front. The relative permeability in the swept region in the models is essentially unity. Therefore, adjustment of the viscosity of the fluids in the unswept and swept regions gives the desired mobility ratios. Naphtha and mixtures of naphtha and mineral oil were used to obtain fluids with the desired viscosities. The injected fluid was forced into the models with a constant rate pump.

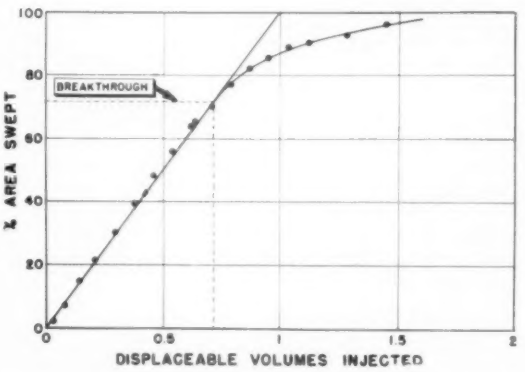

FIG. 2 — BASIC CURVE PLOTTED FROM DATA OBTAINED FROM FIG. 1.

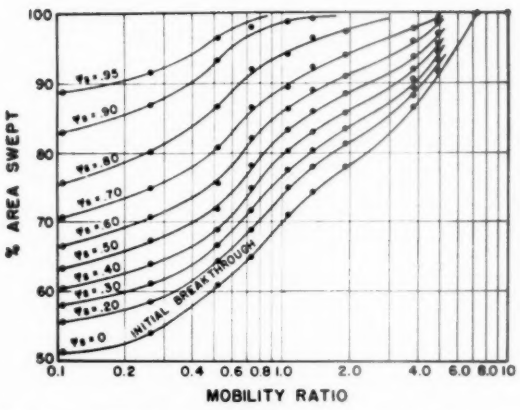

FIG. 3 — EFFECT OF MOBILITY RATIO ON OIL PRODUCTION FOR THE FIVE SPOT PATTERN.

The operational technique involved in these studies will be discussed for a five spot flood in which the mobility ratio was 1.06. The reservoir element represented by the porous model was one-quarter of a five spot pattern. The model was a 5-in. square, having the equivalent of one-quarter of an injection well at one corner and one-quarter of a producing well at the diagonal corner. The fluid viscosities were 1.33 cp for the injected phase and 1.25 cp for the displaced phase. Since the relative permeability to either of the phases is unity, the mobility ratio is 1.06.

In order to analyze the experimental data completely it is necessary to trace the area swept from each radiograph taken during a flood. Fig. 1 shows part of the set of tracings from which the fraction of reservoir area swept at the time of each radiograph is obtained. The increase in area contacted by injected fluid after breakthrough is apparent in this figure. The dotted line shows the position of the flooding front at initial breakthrough of injected fluid. Seventy per cent of the area of the model was swept at this time. The dashed line indicates the position of the flooding front at a later time when 96 per cent of the area had been contacted. The ratio of the flow of injected fluid produced to the total flow from the producing well at this time was 0.87. By the time abandonment conditions (arbitrarily considered as a ratio of 0.95) were reached the model was almost entirely swept.

From the complete set of tracings a basic curve is obtained by plotting the fraction of reservoir area swept versus the number of displaceable volumes which have been injected. The displaceable volume (D_v) is the product of the pore volume of the unit pattern and the displacement efficiency (the change in oil saturation which occurs in the swept region). This curve for the five spot flood being considered is shown in Fig. 2. The point at which this curve deviates from a straight line gives the areal sweepout efficiency at breakthrough of the injected phase. From this curve the information necessary for practical application of the data may be calculated. It can be shown from simple material balance considerations that the fraction of total flow occurring from the unswept region at any time after breakthrough is the slope of the curve at that point. For convenience in calculating water-oil ratios or gas-oil ratios from the laboratory data, the fraction of the total flow occurring from the swept region (Ψ_s) is reported.

The curves shown in Figs. 3 and 4 were obtained from similar flooding experiments on the five spot model. A range of mobility ratios from 0.105 to 17 was covered in this study. The data obtained at mobility ratios less than 0.5 must be considered as only approximate since the injected phase front at low mobility ratios becomes very irregular. These data at mobility ratios less than 0.5 can be considered to represent approximate extensions of the trend developed by the data obtained at higher mobility ratios.

A family of curves shown in Fig. 3 presents the area swept as a function of mobility ratio for increasing values of the fractional flow from the swept region and indicates the area of the reservoir which is contacted at abandonment conditions.

Fig. 4 shows the area swept as a function of mobility ratio and the number of displaceable volumes injected. This is used to predict the total volume of injected fluid necessary to produce a given quantity of oil. The breakthrough curve obtained with the miscible phases differs from that reported by Slobod and Caudle[5] in the region above a mobility ratio of 1. It is felt that this difference arises as a result of the previous data being obtained by the use of immiscible phases. The use of immiscible phases leads to difficulty in assigning a mobility ratio to the system since a small gradient in saturation is probably present behind the front, and this sometimes represents a large gradient in mobility. In addition, it is difficult to define accurately the relative permeability relationships of the model from the relative permeability relationships obtained on smaller samples. The use of miscible phases eliminates these difficulties and yields results which represent regions of uniform mobility and the influence of a known mobility ratio on flood pattern efficiency.

INFLUENCE OF MOBILITY RATIO ON DIRECT AND STAGGERED LINE DRIVE SYSTEMS

In addition to the work described above for the five spot pattern, results have also been obtained for the direct and staggered line drive flooding systems. For both of these systems the ratio of the distance between injection and producing lines to the distance between either producers or injectors was unity.

The results of these studies are shown in Figs. 5 to 8. These data can be used to predict reservoir performance in the manner to be discussed below for the five spot system.

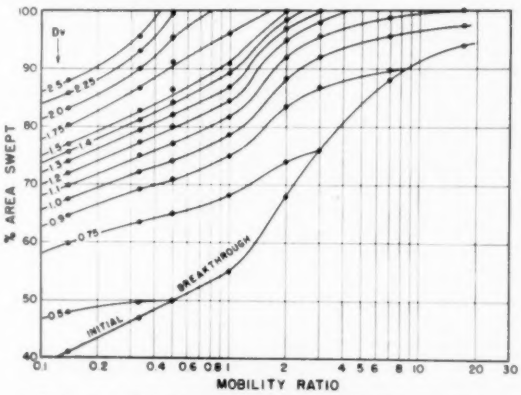

FIG. 4 — EFFECT OF MOBILITY RATIO ON THE DISPLACEABLE VOLUMES INJECTED FOR THE FIVE SPOT PATTERN.

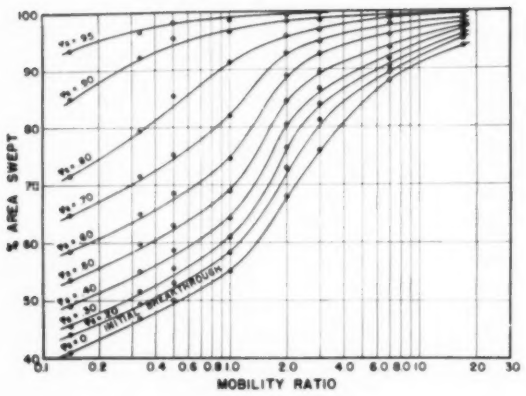

FIG. 5 — EFFECT OF MOBILITY RATIO ON OIL PRODUCTION FOR THE DIRECT LINE DRIVE (SQUARE PATTERN).

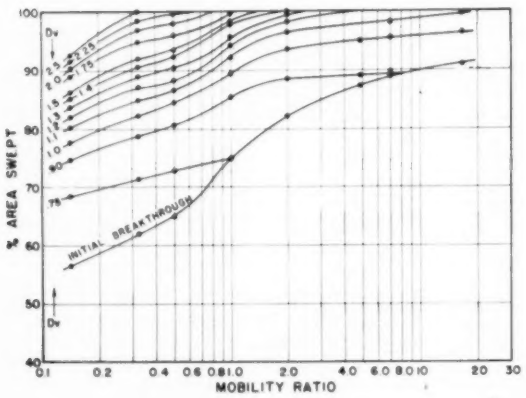

FIG. 6 — EFFECT OF MOBILITY RATIO ON THE DISPLACEABLE VOLUMES INJECTED FOR THE DIRECT LINE DRIVE (SQUARE PATTERN).

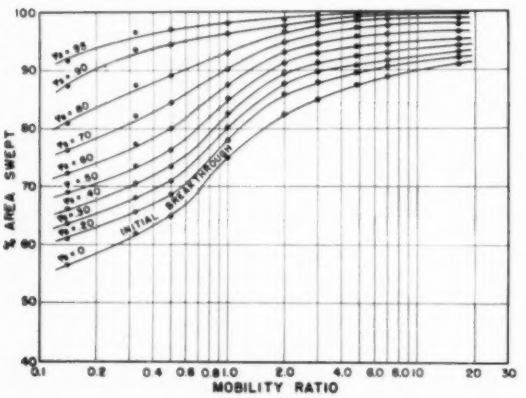

FIG. 7 — EFFECT OF MOBILITY RATIO ON OIL PRODUCTION FOR THE STAGGERED LINE DRIVE.

APPLICATION OF THE LABORATORY DATA TO RESERVOIR ANALYSIS

The data obtained from the laboratory models emphasizes the significant effect which mobility ratio can have on the oil production rate, the water or gas-oil ratio, the ultimate recovery, and the life of an injection operation. The information obtained represents conditions of the model in which the mobility ahead of the front and that behind the front was constant, in which the thickness and absolute permeability are uniform, in which no flow of the displaced phase occurs behind the front, and in which only one mobile phase is present in the unswept region.

These conditions in the model represent a steady-state injection operation and correspond to flooding operations above the bubble point and approximates floods conducted at gas saturations less than critical. The flooding of reservoirs containing high gas saturations and which are characterized by the formation of an "oil bank" is not being treated in this paper.

In practice a large amount of oil is generally thought to be produced from the region behind the front when gas is displacing oil and to a lesser degree when the injection phase is water. For water injection this continued oil production from the swept region frequently appears to be small and is sometimes neglected in engineering studies. In this case the curves presented in the paper can be used directly to describe the production after breakthrough.

EFFECT OF MOBILITY RATIO ON A WATER INJECTION OPERATION

From the basic laboratory results of Figs. 3 through 8 the influence of the mobility ratio on the production rate, producing ratio, cumulative recovery, quantity of injected fluid, and cycled fluid can be obtained for a wide range of mobility ratios. This might best be illustrated by applying these curves in showing the water flood performance of one five spot of an infinite array. Consider 40 acres to be flooded, having a thickness of 20 ft, a porosity of 20 per cent, an initial oil saturation of 70 per cent, an average saturation behind the front of 35 per cent, and an oil formation volume factor of 1.3. The displaceable volume of this five spot pattern would be 435,000 bbls. For an assumed constant injection rate of 200 bbls/day, the time required to inject one displaceable volume would be six years. The difference that could be encountered in field performance in flooding this pattern resulting from differences which might be encountered in mobility ratio for the case which assumes zero flow of oil from the swept region is illustrated in Figs. 9 and 10.

Fig. 9 illustrates the fact that low mobility ratios lead to early declines in the fraction of total flow which is proceeding from the unswept region and therefore result in a less favorable rate of oil recovery. The effect of less favorable rates of recovery at low mobility ratios on the life and cumulative oil recovery is shown in Fig. 10. Considering a 95 per cent water cut to be abandonment, the mobility ratio range of 0.5 to 5.0 would lead to a twofold difference in operating life.

The ultimate oil recovery, however, is near the same from 322,000 to 334,000 bbls. This corresponds to better than 96 per cent sweepout pattern efficiency for the five spot at abandonment conditions over the

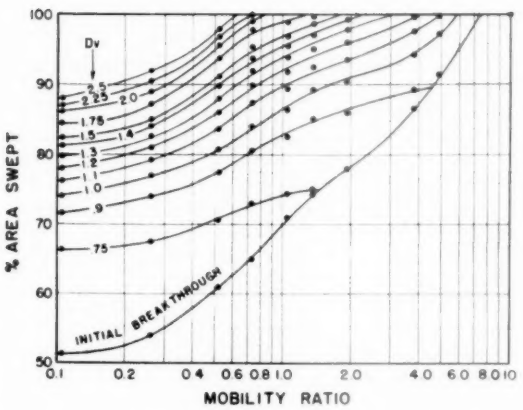

FIG. 8 — EFFECT OF MOBILITY RATIO ON THE DISPLACEMENT VOLUMES INJECTED FOR THE STAGGERED LINE DRIVE.

mobility ratio range of 0.5 to 5.0. At low mobility ratios up to one-half of the recoverable oil may be produced after breakthrough, as can be seen in Fig. 3.

In applying the data obtained on the laboratory models which was reported in terms of reservoir volume flow to the prediction of field performance, it is necessary to convert these data to stock tank conditions. For the case which assumes no oil flow behind the injection phase front, the following equations can be used to account for the formation volume factor of the oil and the solubility of the gas in the oil in expressing the above data in terms of oil rate, gas-oil ratio, water-oil ratio, etc. These equations are for the case in which oil is being displaced by water. Similar equations can be developed for gas cycling operations.

$$R_w = \frac{\Psi_w \beta_o}{1 - \Psi_w}$$

$$C_w = \frac{\Psi_w \beta_o}{1 + \Psi_w (\beta_o - 1)}$$

$$R_g = S$$

$$\Delta N = \frac{E_v V (\rho_{oi} - \rho_{os})}{\beta_o}$$

R_w = water-oil ratio, bbls/STB

β_o = oil formation volume factor, $\frac{\text{res bbls}}{\text{STB}}$

Ψ_w = fraction of total reservoir flow from swept region, $\frac{\text{res bbls}}{\text{res bbls}}$

C_w = water cut, water fraction of gross separator liquid

R_g = gas-oil ratio SCF/STB

S = solubility of gas in oil under reservoir conditions, SCF/STB

ΔN = oil production STB

E_v = fractional sweepout pattern efficiency

V = pore space of elemental pattern, bbls

ρ_{oi} = initial oil saturation, fractional pore space

ρ_{os} = oil saturation in swept region, fractional pore space

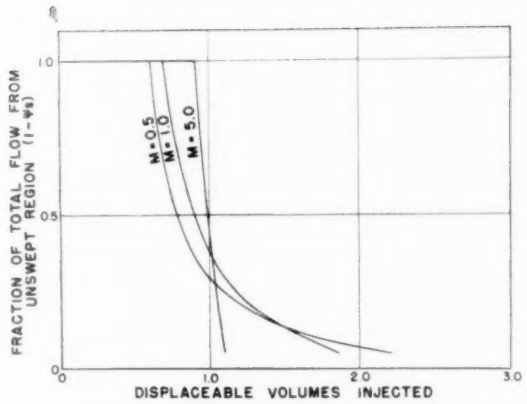

FIG. 9 — INFLUENCE OF MOBILITY RATIO ON OIL PRODUCTION FROM UNSWEPT REGIONS IN A FIVE SPOT PATTERN.

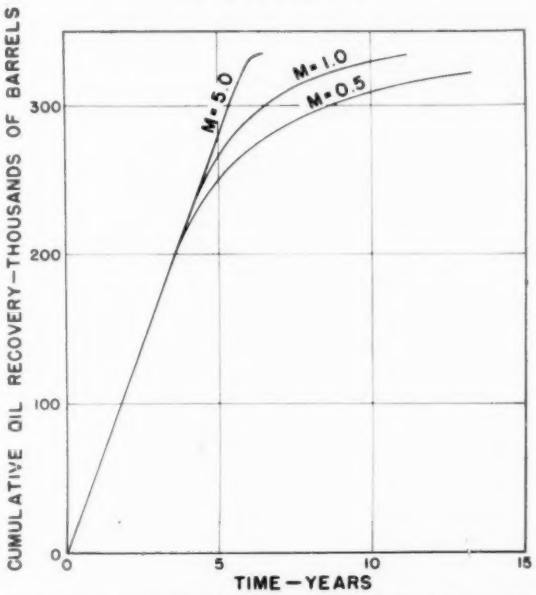

FIG. 10 — ILLUSTRATION OF THE INFLUENCE OF MOBILITY RATIO ON THE CUMULATIVE OIL RECOVERY FROM THE FLOOD OF ONE FIVE SPOT (40 ACRES, THICKNESS 20 FT, POROSITY 20 PER CENT, INITIAL OIL SATURATION 70 PER CENT, FINAL OIL SATURATION BEHIND THE FRONT 35 PER CENT, FORMATION VOLUME FACTOR OF 1.3).

APPLICATION OF LABORATORY DATA TO GAS INJECTION OPERATIONS

The saturation gradient which is believed to be present in operations involving the displacement of oil by gas complicates the simple application of the laboratory data to field performance by introducing such factors as: (1) a gradient in the fluid mobility behind the front, and (2) the flow and consequent production of oil from behind the front. In the laboratory floods it has been observed that the front remains radial during the encroachment into the first 15 to 25 per cent of the area of the model for all mobility ratios. This suggests that the mobility near the injection well has much less influence on the

sweepout pattern efficiency than that which is present near the front in the area in which flow ceases to be radial. Until a quantitative method is developed to consider properly the gradient in the fluid mobilities present in the reservoir, it is suggested that a series average of the fluid mobilities between the front and the injection well be used in defining the average mobility of this region. By this means the fluid mobility near the injection phase front is given more weight.

The application of relative permeability relationships to the displacement of oil by gas shows continued production of oil from areas after invasion by the gas. This production which occurs in the region behind the front must be considered in applying the data presented in this paper to the engineering calculations of field performance. No rapid and easy solution which accurately defines the oil flow from the swept region after breakthrough in a pattern flood as a function of the volume injected or areal sweepout efficiency can be presented at this time. The flow from this region can perhaps be approximated sufficiently well for engineering purposes by calculating the oil saturation in the swept region and the fraction of oil flow behind the front by the application of the method of Buckley and Leverett,[7] which was developed for a linear flow system.

Many factors influence the ultimate fraction of the reservoir to be swept by an injected phase at abandonment conditions. The information presented here shows the effect of one of the variables, that of mobility ratio. This is a property specific to a given flood and its influence must be considered by the reservoir engineers in arriving at an estimate of total oil to be recovered. The influence of other features of the reservoir, such as sand continuity, number of sand members present, permeability variations, irregular well pattern, and amount of oil beyond the boundary wells, etc., must also be considered by the reservoir engineer in arriving at an estimate of the fraction of the reservoir to be ultimately swept by the injected phase. For any given system, however, that estimate should include the performance following breakthrough and leading up to abandonment conditions.

CONCLUSIONS

The results of this study of the influence of the mobility ratio on the oil production after breakthrough lead to the following conclusions:

1. Over the wide range of mobility ratios which may be encountered in injection operations there can frequently be as much as 50 per cent of the ultimate oil recovery obtained after breakthrough.

2. Although high ultimate sweepout pattern efficiencies are obtained (85-100 per cent) for most mobility ratios encountered in field operations, the economic aspects of the rate of oil recovery and the total amount of fluid to be injected cause the higher mobility ratio floods to be much more favorable.

3. The inclusion of the production after breakthrough which results from a continual enlargement of the sweepout pattern is essential in making a comparison between different plans of operation.

4. The data presented here showing the contribution from the unswept region to the oil production after breakthrough can be combined with observed water flood behavior to give the engineer a means of gaining knowledge concerning the magnitude of oil flow behind an invasion front and knowledge of the possible influence of permeability stratification on the flood.

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DRILLING MUD CONTROL in the SOUTHWEST LOUISIANA COASTAL AREA

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T. P. 3783

ABSTRACT

Since March 1945, the Magnolia Petroleum Co. has drilled 39 wells in Southwest Coastal Louisiana. All wells were drilled within a comparatively small radius, but the area provides a large variety of problems. The deepest well drilled was 13,518 ft, and the total depth averaged 10,977 ft. Throughout this period drilling mud control and types of mud handled were: (1) phosphate, (2) red lime (late conversion), (3) red lime starch (early conversion), (4) red lime starch oil emulsion, (5) precision controlled low alkalinity-low lime content, and (6) gel muds for completion purposes.

Improvement has been obtained in effecting some or all of the following: (1) more rapid penetration, (2) reduction in drilling hazards, (3) better evaluation of cores and logs, and (4) better completions.

The geological sequence of zones penetrated range from recent sediments at the grass roots through the Frio section. Anticipation of high-pressure zones and incompetent formations entails precision control of drilling mud weights, and the unconsolidated nature of the various zones requires constant attention to the filtrate, viscosity, and gel strength values. In the Chalkley field, particularly, this combination of problems exists, where the formation pressures and overburden weight density values are in very close proximity. Design of casing and drilling mud programs must be modified to fit each well.

INTRODUCTION

Field and research work on drilling fluids has made constant progress, enabling operators to prospect progressively deeper horizons. Numerous papers have been written on the theoretical aspects of drilling fluid development, but in the field engineers have found it difficult to evaluate the role of specific mud constitutents when dealing in terms of thousand barrel mud systems. For that reason field data is somewhat lagging in technical report writing. However, applications of new techniques in the field have usually paralleled, and in numerous instances preceded, research work.

The information obtained by Magnolia Petroleum Co. in the course of drilling 39 wells within a comparatively small area in Southwest Coastal Louisiana provides an excellent opportunity of reviewing a specific example of drilling mud evolution. A large variety of problems has been coped with, the most important result being that every well was successfully drilled to its projected total depth. The discussion begins with the advent of deep drilling in this area in March, 1945, and is concluded with a resume of recent drilling operations in the Chalkley field.

The primary purpose of this paper is to describe the evolution in types of drilling fluids as it occurred and its application in the solution of various drilling problems. All of this information and experience resulted in the successful drilling of the three wells in the Chalkley field, where a combination of the most sound techniques was necessary in carrying drilling operations to the projected total depths. Other operators along with service company engineers have contributed considerably through the interchange of ideas and information to this paper, but the data and conclusions which are contained are based on first-hand observation of Magnolia Petroleum Company's drilling operations.

The 39 wells drilled by Magnolia Petroleum Co. average in depth 10,977 ft per well, while the maximum depth penetrated was 13,518 ft. The cost of drilling fluids have varied from $8,700 to $165,000, with the over-all drilling costs ranging from $74,000 to $543,000 per well. This wide variance illustrates the unpredictable nature of each well and the effects on over-all cost when high density muds are required to control

[1]References given at end of paper.

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SERIES	GROUP	FAUNAL ZONES
RECENT	UNDIFFERENTIATED	
PLIOCENE	UNDIFFERENTIATED	
MIOCENE		Bigenerina humblei
		Amphistegina (B)
		Discorbis bolivarensis
		Siphonina davisi
		Planulina palmerae
		Abbeville assemblage
		Discorbis (large)
		Heterostegina sp.
		Bolivina perca
		Marginulina idiomorpha
		Marginulina vaginata
		Marginulina howei
		Camerina (A)
		Cibicides hazzardi
		Marginulina texana
		Hackberry assemblage
		Nodosaria blanpiedi
OLIGOCENE	VICKSBURG	

FIG. 1 — TENTATIVE STRATIGRAPHIC COLUMN OF CAMERON PARISH, LA.

abnormal pressures. The usual major potential sources of difficulty anticipated in drilling are loss of circulation, stuck pipe, blow-outs, salt water flows, formation sloughing, and crooked holes. The geological interpretations of coastal Louisiana are very complex, but an appreciation by mud engineers of the geological facts is important.

GEOLOGY

The stratigraphic section penetrated includes Recent, Pleistocene, Pliocene and Miocene deposits. This section consists of sand and shales interspersed with occasional thin shell beds and lime zones. The shales contain an abundance of mud-making constituents. The sands vary considerably in grain size and assortment and in degree of cementation. The lime and shell beds are not quite so prominent, but probably are responsible for a lot of the mud troubles because of the porous nature of the shell beds, which are found at any depth ranging from the grass roots to the maximum depths penetrated.

Difficulties are sometimes experienced in correlating from well to well, especially in the upper Miocene section which consists predominately of massive sands. Paleontological markers are used in defining the zones penetrated. These are listed in the geological section shown in Fig. 1.

The type of deposition varies. The lower Miocene is entirely marine, the upper Miocene is somewhat less than half marine, and the Pliocene and Recent are entirely continental deposits. Tectonic movements along hinge lines and upthrusts of salt masses have caused abnormal accumulation of sand in localized areas. When these sands occur as lenses, or are faulted against shale, abnormal pressures are often encountered. This is caused by the hydrocarbons and salt water contained in the shale deposits being forced by sheer overburden weight into available pore space where they had no subsequent path of escape.[1]

Structures in the area under discussion are the result of regional faulting and deepseated salt intrusions. Which of the two is responsible for the oil and gas accumulations in some of the fields under review is debatable, but it is not within the province of this paper to delve into that problem. It is sufficient to state that adequate structural relief has been found which could provide traps for the economic accumulations of hydrocarbons.

Geophysical methods, most reflection seismograph surveys and subsurface work, were responsible for discovering the anomalies. High pressure zones are found starting with the Planulina and Abbeville sections, with depth playing an important factor in the degree of pressure abnormality. Only those wells drilled on the crest of structures have completely penetrated the Abbeville section, as a tremendous thickening occurs on the flank downdip toward the Gulf of Mexico. The unpredictable depths at which prospective producing sands would be found beneath that zone on the coast have not yet warranted exploration efforts.

The tremendous role that the Abbeville section plays is best exemplified by the recent drilling in the Chalkley field. There only a very thin section was penetrated in the exploration of high-pressure-producing sands that are found below it in the Camerina and Cibicides Hazardi zones.

GEL-PHOSPHATE SYSTEMS

Prior to 1945 numerous shallow wells were drilled in Cameron Parish that did not require very close mud control. Deep-well drilling began in March, 1945, when the Lutcher A-1 was spudded in the Mud Lake area. The type mud customarily used at that time consisted of gel and native clay solids treated with phosphate and caustic-quebracho for viscosity and water loss control. Other chemicals were used, but mostly in a minor role, as retarding agents to phosphate deterioration. The time required to drill the Lutcher A-1 with this type mud to a total depth of 11,932 ft was 145 drilling days, with a drilling fluid material cost of approximately $33,000. Included in the 145 drilling days were eight days consumed in mud conditioning time that is not reflected in the cost of the drilling fluids. This mud conditioning time was caused by complications encountered in controlling rheological properties of the high density mud (16 lb/gal.), which was required to contain the abnormal formation pressures.

LIME-BASE MUDS

An advance in mud treatment occurred in early 1949. While drilling the Lutcher C-1 in the East Mud Lake field with a conventional phosphate mud at a depth of 11,012 ft, casing was set in anticipation of high pressure zones. Previously, difficulties in controlling mud properties at these depths and temperatures had been encountered. Therefore, in an effort to eliminate or reduce operational difficulties, the mud was converted to a high pH caustic-quebracho system and lime was employed to control gels and viscosities. This probably was the equivalent of our present concept of a lime-treated mud. Maximum mud weight was 13.2 lb/gal.

The well was then carried to a total depth of 11,707 ft without undue incident. At no time was there any trouble getting to bottom with drill pipe, logging tools or liner while using this type of mud. Drilling time was 95 days with a mud and chemical cost of $19,439. Also, it was concluded, and proved by subsequent drilling, that the hole would stand up for much longer periods of time with lime-treated or lime-base muds than with the previously employed systems.

The practice of using small lime additions in treating

red muds was short-lived, as control was found to be simplified by converting with excess lime, estimated at 4 to 12 lb/bbl, and continuing with large per tour treatments to maintain this value.[2] For a while it became a standard procedure for Magnolia to convert muds to lime base muds when drilling had reached approximately 8,000 ft.

Further simplification in mud control was the convenient expedient of converting muds at shallow depths when the percentage of solids was low, rather than at the 8,000 to 10,000 ft depth range. Surface casing in these wells in the subject area is usually set at 4,500 ft, which lends itself perfectly to a lime change-over at this point, while drilling cement, without the difficulty often encountered. This practice was started in March, 1949, and has become routine with conversion accomplished in several circulations. It has resulted in substantial savings in rig time and mud costs over the period.

OIL-EMULSION MUDS

Oil-emulsion muds were introduced in December, 1949, while drilling a directional hole on State of Louisiana Lease 1120 A-1 in the Holly Beach field. The hole tried to grab the drill pipe while drilling at 9,000 ft with a 3.5 cc water loss lime-base mud. The system was then emulsified with 10 per cent diesel oil which reduced the water loss to less than 1 cc. In 13 days 1,550 ft (9,390 ft - 10,940 ft) were drilled for an average of 119 ft/day, an outstanding record compared to straight hole drilling at equivalent depths where the previous fastest drilling rate was 84 ft/day. Sixty days were required to drill to 10,940 ft with a drilling fluid cost of only $16,422. Prior to this well the geologists had not given the "green light" to the use of oil in muds because of the uncertainty as to its effect on cuttings, core and electric log interpretations. Their objections have since been withdrawn, as with experience they have been able to differentiate between diesel oil and formation hydrocarbons.

Oil emulsion mud is being used quite often to speed drilling time. Its chief use, however, is in straight or directional holes where comparatively high filtrate loss of the muds or crooked hole conditions cause sloughing.[3] The volume percentage of oil has ranged as high as 16, but mud properties are easier to control when the oil content is around 10 per cent.

LIME TREATED MUDS

The development of methods for determining free lime content has been valuable to the mud engineer in controlling the lime systems.[4] As a direct result of mud control work in these wells Magnolia Laboratories was prompted to work on this problem. A method for determining the lime content and alkalinity level of drilling fluids has been developed and accepted for field use.[5] This method requires separate chemical titration of the drilling fluid and the drilling fluid filtrate.[6] As a result of this determination, it is no longer necessary to continue the practice of making heavy lime conversions or per tour treatments simply to be sure the lime concentration is sufficiently high. Reduced and more carefully considered additions are the rule.

The logical sequence in the treating evolution was the re-investigation of the commercial and practical aspects of reverting to moderately-high pH caustic-quebracho systems using lime only as a control agent.[7]

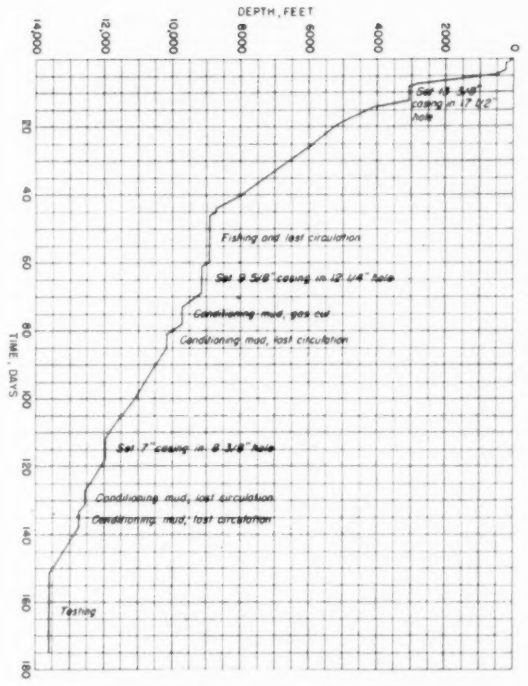

FIG. 2 — GRAPHIC DRILLING RATE, SWEETLAKE B-1, CHALKLEY FIELD.

The remarkable success of such controlled application is typified in the Sweetlake B-3 well in the Chalkley field. The initial conversion and a typical mud check along with a recommended per tour treatment for this type mud is shown in Table 1.

While lime base systems had definite advantages over phosphate-treated muds insofar as viscosity and gels were concerned, the inability to run logging and perforating instruments to bottom in the deeper wells was experienced. Maximum temperature recorded at 13,515 ft was 262°F. The average gradient is 1.4°/100 ft of depth. Conclusive evidence that the mud was actually forming a cement-like material was found. Excessive lime content in the presence of high alkalinities caused this. Lime-treated mud offered the best solution to the problem of drilling deep, hot holes.

It had been customary in deep wells where high-temperature gelation was likely to occur to prepare a

TABLE 1 — INITIAL CONVERSION, TOUR TREATMENT AND TYPICAL MUD PROPERTIES OF MUD USED ON THE SWEETLAKE B-3

	Initial Conversion, lb/bbl	Tour Treatment, lb
Caustic Soda	1	50
Quebracho	3	100
Lime	2	50
C M C	1	As needed to maintain filtrate below 5 cc

MUD PROPERTIES	
Weight, lb/gal	17.8
Viscosity, Funnel, Sec.	53
Viscosity, Plastic, cp.	40
Yield value, lb/100 sq ft	8
Initial Gel., grams	0
10-minute gel, grams	1
pH	11.8
Filter loss, API, cc	4.8
Cake, 32nd in	3
Lime, lb/bbl	0.5
Filtrate Analysis:	
Alkalinity, P	1.0
M	2.9
Chloride, ppm	1800

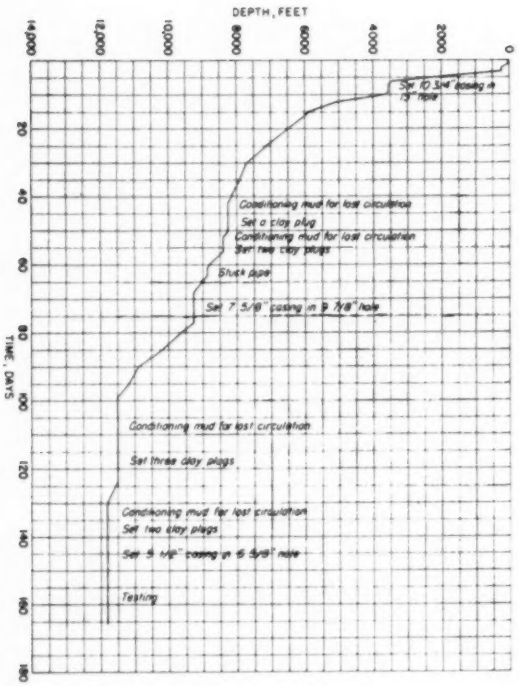

FIG. 3 — GRAPHIC DRILLING RATE, SWEETLAKE B-2, CHALKLEY FIELD.

low bentonite content behind the packer mud, weighted to the desired value. The only chemical used in this method is caustic soda, for pH control to minimize corrosion and also to accelerate the yield of the bentonite. A tremendous handicap encountered in this practice is the lack of tolerance for cement contamination, or the expense of having to revert to the original mud system if a cement squeeze job should become necessary. Rigtime and cost of materials to prepare an 18 lb/gal. mud for the B-3 well would have been, roughly, $8,000.

Field tests were conducted with both the lime-treated mud used in drilling and a laboratory-prepared low-percentage bentonite mud. At an elevated temperature over a 48-hour period the two muds checked closely in their ability to revert to fluidity. The well completion was made with the original mud, resulting, therefore, in the savings of the estimated $8,000. Another advantage of the lime treated system is in the obtention of higher resistivity values for better electric logging results. At 100°F the resistivity value of the lime base mud in Sweetlake B-1 and the lime treated mud in Sweetlake B-3 were 0.48 ohmmeter and 1.4 ohmmeter, respectively.

CHALKLEY FIELD

Probably the most difficult drilling in this area is in the Chalkley field, because of the proximity of formation pressures to overburden pressure. Sand objectives are not particularly deep compared with the average drilling depth of wells in South Louisiana, but depths are a relative matter where abnormal pressures and related hazards are concerned. Attesting to this fact is the high mortality rate of wells drilled below 10,000 ft in this field. At approximately 8,000 ft, pressures are abnormal. By the time 11,000 ft has been reached, formation pressures are near the rupture point of the overburden.

In Sweetlake B-1 the calculated static bottom hole pressure was 10,260 psi at 11,806 ft. This formation was penetrated with 17.5 lb/gal. mud which provided a differential of approximately 480 psi. The precarious nature of such a close differential is illustrated by the problem that faced the authors at the start of drilling the B-2 well. Geologists estimated that the high pressure zone would be encountered some 200 ft higher than B-1, which meant a 183 psi reduction of the 480 psi hydrostatic head differential using a 17.5 lb/gal. mud system. Therefore, 18 lb/gal. mud weight was recommended to compensate for the structural difference and to provide an added factor of safety for mechanical operations in the proposed reduced hole size. The rupture point of the overburden below 11,000 ft, however, was found to be slightly higher than the hydrostatic head equivalent of 17.8 lb/gal. mud, both during actual drilling in this well and in the subsequent drilling of the Sweetlake B-3. Equally important in the pressure consideration was attention to casing points, mud properties and drilling techniques in order to minimize the chances of causing any undue pressure surge against the hole. The actual casing and mud programs for the three wells drilled in the Chalkley field are shown in Table 2.

SWEETLAKE B-1 WELL

A brief history of the Sweetlake B-1 well is as follows: At 5,500 ft the mud was converted to a 10 per cent oil-emulsion, lime-base system. Mud weight was increased at approximately 8,600 ft from 12 to 13 lb/gal. because of gas cutting after trips. Lost circulation occurred at 8,889 ft and, as fibrous material was added, the shaker was by-passed and drilling was carried to 9,100 ft. There the casing was set while using 14 lb/gal. mud. The 9⅝-in. plug was drilled with 16.5 lb/gal. mud. Drilling continued without incident to the 7 in. casing point at 11,965 ft during which time the mud weight had been gradually increased to 17.5 lb/gal. In drilling out of the 7 in. casing to the 13,517 ft total depth, the weight varied between 17.5 to 17.7 lb/gal. The shale shaker was by-passed during the entire drilling operation from the 9⅝-in. casing point to the total depth to maintain a high concentration of lost circulation materials.

Viscosities could only be controlled through water additions which explains the $164,000 mud and chemical costs. Casing or liner was not set at total depth, for the well was completed through perforation 11,803-11,807 ft in the 7 in. casing as a gas-distillate producer. It had a shut-in tubing pressure of 8,695 psi. The serious danger of drilling the B-1 with the small hydrostatic pressure differential was only realized during testing operations in pipe.

TABLE 2 — CASING PROGRAMS USED IN THE CHALKLEY FIELD

	Sweetlake B-1		Sweetlake B-2		Sweetlake B-3	
	Size, in.	Depth, ft	Size, in.	Depth, ft	Size, in.	Depth, ft
Conductor	20	221	16	252	20	253
Surface	13⅜	3,011	10¾	3,505	13⅜	3,487
Intermediate	9⅝	9,119	7⅝	9,243	9⅝	9,063
Production	7	11,965	5½	11,740	7	11,198
Liner					5	10,931–11,943

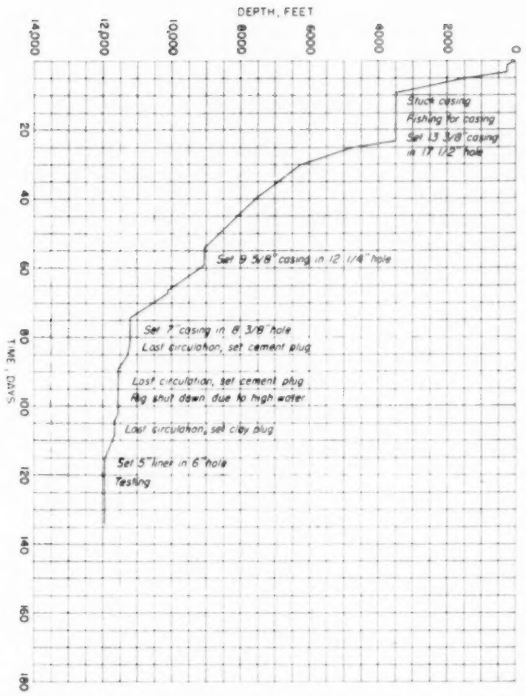

FIG. 4 — GRAPHIC DRILLING RATE, SWEETLAKE B-3, CHALKLEY FIELD.

SWEETLAKE B-2 WELL

A further curtailment in the casing program for B-2 became necessary, however. Because of a critical pipe shortage at the start of B-2, hole and pipe diameters were reduced from those employed in B-1. Again the plan was to drill substantially below the 9,119 ft casing point equivalent of B-1 and to case off most of the intermediate high pressure and heaving shale zones. Lost returns forced the casing to be set at 9,243 ft. First, 17 lb/gal. mud was used from that point; then 18 lb/gal. was in use by the time 10,000 ft had been reached. This was done in order to learn whether the formations would withstand this weight mud prior to drilling the 11,800 ft sand. Continued lost return difficulties at 11,800 ft forced the setting of 5½-in. casing after the high pressure sands were found beneath the gas-water contact.

Comparative analyses of both drilling and mud costs for the B-1 and B-2 wells show conclusively that the reduced hole size increased over-all drilling and mud costs. Cost of mud materials per foot was $12.20 and $12.63 for B-1 and B-2, respectively, while intangible drilling costs for the same wells were $34.29 and $36.29, respectively. Fig. 5 illustrates drilling rates at the various depths for all three wells.

SWEETLAKE B-3 WELL

Drilling costs for B-1 and B-2 were such that the economic feasibility of further developing the 11,800 ft sand was questioned. Only the possibility of encountering multiple sand reservoirs favored the drilling of B-3. Reduction in mud materials and drilling costs were mandatory in calculating a pay-out, and the design of the mud and casing programs to reduce these costs incorporated the following recommendations:

(1) Drill with mud weights compatible with both the competency of the formations and the abnormal pressure zones down to the 9,628 ft equivalent of B-1.

(2) Establish close casing point control by electric log, because every foot of hole cased would eliminate a future source of danger from shale sloughing or lost returns.

(3) Add a magnetic tracer material to the mud system at approximately 8,000 ft and maintain a proper concentration of this tracer to the total depth. In case of lost circulation, run a magnetic induction log to determine the exact point of mud loss by measuring variations in magnetic intensity; then spot time-setting clay cement in that zone to restore circulation.

(4) Set 7 in. casing at approximately 11,100 ft in anticipation of the two known high pressure zones found in the B-1 at 11,400 ft and 11,800 ft.

(5) Use a lime treated mud in drilling to the projected total depth and maintain this mud in a condition that would be satisfactory for completion purposes.

The above recommendations were followed with minor deviations in the drilling of the Sweetlake B-3 well. The result of this planning was that both the mud costs and intangible drilling costs were reduced approximately 31 per cent from those of the two previous wells. Drilling to the total depth required 89 days at a drilling and mud cost of $287,712 and $102,176, respectively. Although the same massive mud making shale formations were encountered in B-3, the lime treated mud did not result in any difficulty in viscosity control. In fact, the viscometric properties were very much better, as evidenced by the over-all reduction in mud costs. Table 3 reflects the percentage

TABLE 3 — PER CENT OF THE TOTAL COST OF THE MUD CONSTITUENTS USED IN DRILLING EACH WELL IN THE CHALKLEY FIELD

	Sweetlake B-1 per cent	Sweetlake B-2 per cent	Sweetlake B-3 per cent	Field Total per cent
Weighting Materials	73.10	69.90	81.44	74.23
Clays	1.22	1.10	0.91	1.09
Chemicals	11.01	9.23	6.91	9.05
Lost Circulation Materials	6.39	15.67	4.69	9.89
Water Loss Reducing Additives	8.38	4.10	6.05	5.74
	100.00	100.00	100.00	100.00

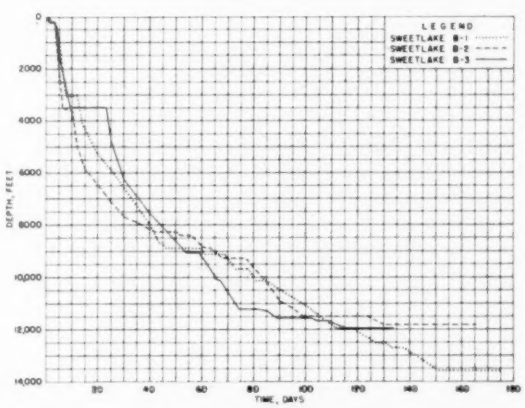

FIG. 5 — COMPARISON OF DRILLING RATES IN THE CHALKLEY FIELD.

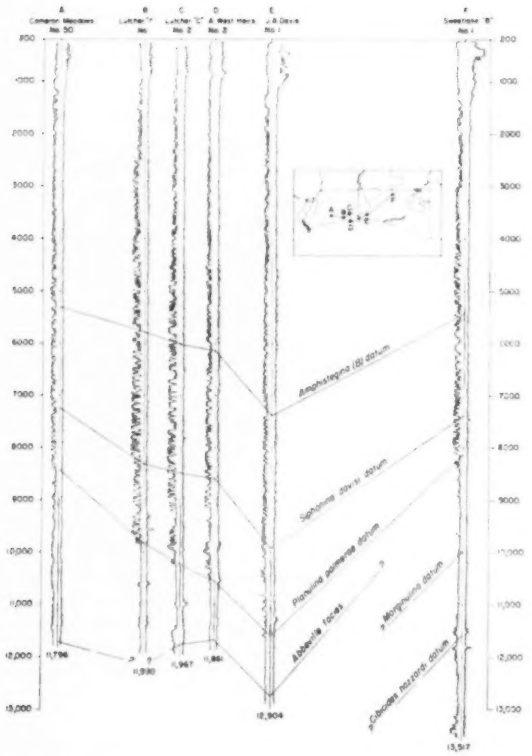

FIG. 6 — WEST-EAST CROSS SECTION OF SOUTHWEST COASTAL LOUISIANA.

of total costs of the mud constituents used in drilling the three wells in Chalkley field.

SUMMARY

Through experience gained in drilling wells since 1945 in Southwest Coastal Louisiana, field engineers and laboratory technicians have improved drilling mud control techniques. Within a small area many different problems were encountered that were successfully handled. Many kinds of mud systems were employed in drilling the wells, each of which has its merits. No one type can be satisfactorily used for all purposes. From an economical standpoint, the lime treated mud offers numerous advantages.

The knowledge accumulated during the period was applied in the planning and the concluding of the drilling of three wells in the Chalkley field, where the most severe drilling hazards of any of the fields under review were found. The experience gained in drilling the first two wells in that field enabled the drilling of Sweetlake B-3 well with a 31 per cent reduction in both drilling and drilling mud costs. Cost reduction is vitally necessary in any drilling operations, but it is particularly important in the development of structures where abnormally-pressured, relatively-thin producing sand zones are marginal in calculated pay-out.

ACKNOWLEDGMENT

Grateful acknowledgment is made for the aid given by the personnel of the Petroleum Engineering, Geological, Production and Drilling Departments, and the Field Research Laboratories of the Magnolia Petroleum Co. Deserving special mention is A. L. Backlund.

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MECHANICAL TREATMENT of WEIGHTED DRILLING MUDS

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ABSTRACT

Maintenance of desirable plastic flow properties of weighted drilling muds may be greatly simplified by use of centrifugal classification to control the drilled solids content. The new application of a decanting type centrifuge to separate and reject the low density solids from the weighting material results in a drilling mud of greatly improved quality with lower values of yield and rigidity.

Its practicality and economy has been proven in field operation. The degree of separation of light and heavy solids is not limited by the machine, but by the particle size distribution of the solids in the mud. Removal of the low density component of drilling mud that makes chemical treatment necessary permits a marked reduction in chemicals.

The main uses of the centrifugal process are the treatment of muds while drilling, the reclaiming of discarded muds, cleaning up of workover muds, and the reduction in lime content of mud for completion.

INTRODUCTION

Drilling mud in any circulatory system is made viscous and difficult to pump by gradual accumulation of drilled solids which pass through the shale shaker and are continually reground. In a weighted mud containing a large proportion of barite by volume, the amount of drilled solids that may be tolerated is greatly reduced. Much effort has been expended to control by chemical treatment the effects of such solids. Though chemical treatment is quite effective, the time eventually comes at deeper depths after enough drilled solids have entered the system when a portion of the mud must be discarded and replaced with water and more weighting material. Once begun, this process is generally continued at frequent intervals with resultant high maintenance costs.

At the termination of drilling, mud highly contaminated with light solids and spent chemicals is poorly suited for completion operations.[1] It is likewise limited in utility for other drilling operations.

This investigation was conducted for the primary purpose of determining an acceptable mechanical means of removing the lightweight solids from weighted drilling muds in order to maintain viscosity at a minimum. A decanting type of centrifuge was selected from the various possible methods of mechanical separation.

The centrifugal process has been employed in this country for this purpose in central mud reclamation systems in California in earlier years. It also was used for treatment of weighted muds on the Gulf Coast.[2] In more recent years only sporadic attempts have been made to employ it in the field on weighted muds.

DISCUSSION OF PROCESS

Selection of Apparatus

Two factors favor mechanical procedure for the separation and removal of drilled solids or clays from the mud circulatory system. First, the greater specific gravity, 4.1 to 4.3, of the barite would promote more rapid settling than the clays whose specific gravity range is from 2.5 to 2.7. Second, the relative coarseness of the barite particles also facilitate faster settling of this phase.

A decanting type of centrifuge was preferred for this process over other possible methods for these reasons:

1. Requires no costly additives or excess dilution.
2. Centrifugal force affords greatly accelerated separation as compared to gravity.

[1]References given at end of paper.

Manuscript received in the Petroleum Branch office Aug. 28, 1953. Paper presented at the Petroleum Branch Fall Meeting at Dallas, Tex., Oct. 18-21.

3. More compact and greater portability.
4. Unaffected by fairly coarse material.

Requirements

In order to fulfill field needs, any centrifugal machine must meet the following:

1. Must make desired degree of separation between drilled solids and weighting material. Excess loss of barite cannot be tolerated.
2. Operation must be continuous and trouble free, with a minimum of operating personnel and maintenance.
3. Should be resistant to abrasion and corrosion.
4. Must operate with minimum of water dilution.

Description and Method of Operation

The centrifuge selected was of the conical decanting type. Its operating principle is illustrated in Fig. 1.

The mechanism shown in Fig. 3 consists essentially of a helical screw conveyor rotating inside a conical bowl, which also revolves in the same direction at a slightly higher speed. The speed of rotation of the bowl creates a high centrifugal force acting at right angles to the axis of rotation.

Diluted drilling mud enters the bowl through a stationary feed tube, as shown in Fig. 1, located in a hollow center shaft. The heavier barite particles, acted upon by centrifugal force, are thrown outward and deposited against the wall of the bowl. The clays and liquid, being of lower specific gravity, form a concentric inner layer in the bowl.

The barite deposited against the bowl is conveyed to the narrow end of the bowl by the pitch and the forward rotation of the helix relative to the bowl, where it is discharged through ports that are suitably located. The barite sludge is returned to the mud tank.

The clays and liquid referred to as effluent or underflow in this discussion are rejected through ports at the opposite end of the bowl.

FIELD RESULTS

Type of Separation Obtained

Field trial of the decanting type centrifuge demonstrated that any desired degree of separation could be effected, commensurate with the particle size distribution of the two solid phases in the system, by varying the rotating speed. This is illustrated diagrammatically in Fig. 2.

At a high rate of speed (point 1 on the curve), the centrifuge would reject all liquid with the effluent or overflow with all of the solids going to the underflow. At a reduced speed corresponding to point 2, a substantial portion of the clays would be rejected with the effluent, and the coarser clays and all of the barite would be returned with the underflow. At a further reduced speed (point 3), a still greater portion of the clays and some of the finer barite will be thrown out with the effluent. This latter point corresponds to the desired operating speed.

It can be visualized from Fig. 2 that an exceptionally high density of solids in the underflow is indicative of inefficient operation.

Table 1 is presented to show the effectiveness of separation that was secured when concentrating 12.5 lbs/gal. mud to 22 lbs/gal. This is best illustrated from the following summary, taken from the table:

Bowl Speed rpm	Per Cent of Total Clays Rejected	Per Cent of Total Barite Lost
1,470 - 1,500	73.7	9.44
1,736	67.6	4.88
2,070	66.4	0.09

Table 1 also substantiates the foregoing theory that density of the solids in the underflow decreases with increasing bowl speeds.

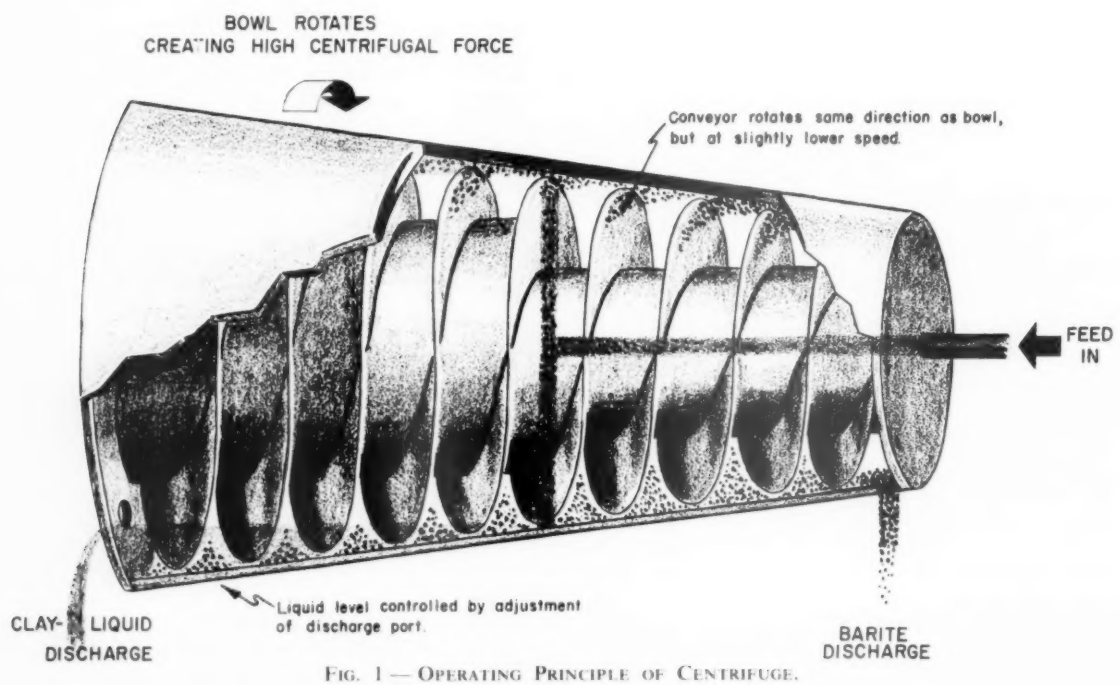
BOWL ROTATES
CREATING HIGH CENTRIFUGAL FORCE
Conveyor rotates same direction as bowl, but at slightly lower speed.
FEED IN
Liquid level controlled by adjustment of discharge port.
CLAY-LIQUID DISCHARGE
BARITE DISCHARGE

Fig. 1 — Operating Principle of Centrifuge.

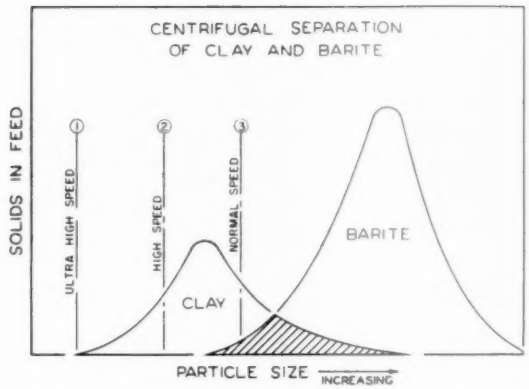

FIG. 2 — CHART, CENTRIFUGAL SEPARATION OF CLAY AND BARITE.

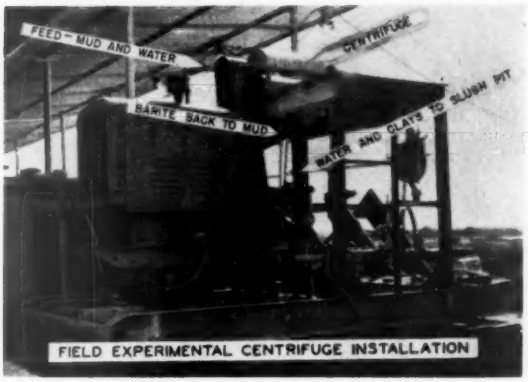
FEED - MUD AND WATER
CENTRIFUGE
BARITE BACK TO MUD
WATER AND CLAYS TO SLUSH PIT
FIELD EXPERIMENTAL CENTRIFUGE INSTALLATION

FIG. 3 — FIELD EXPERIMENTAL CENTRIFUGE INSTALLATION.

OPERATING FEATURES

The experimental gas-engine driven centrifuge installation is shown in Fig. 3. Mud to be processed was delivered to the centrifuge from a forward pit by a separately driven model 1L4 type CDQ Moyno pump. Water from a centrifugal pump was mixed with the mud. The feed thus mixed traversed 50 diameters of pipe in turbulent flow prior to entry into the centrifuge. Barite sludge from the centrifuge was jetted back to one of the mud pits. Rejected clays and water flowed by gravity to a waste pit.

No operational difficulty occurred when processing screened mud. Occasional shut-down resulted on reclamation of gelled mud due to plugging of the intake to a small supply pump with large clods, metallic objects, and other debris. However, the centrifuge handled all material that was fed to it without clogging and without difficulty. The machine was dismantled at the end of 1,000 hours of operation and no wear could be detected by micrometer measurement.

The capacity of a decanting type centrifuge is limited by the quantity of barite sludge than can be conveyed to the discharge end of the bowl. For this reason, mud having a density of 13 lb/gal. can be processed at a greater rate than 18 lb/gal. mud, the comparative throughput depending upon the relative amount of barite and coarse clays which are contained. A protective torque release prevents overloading.

A typical pumper's grind-out centrifuge was quite useful in estimating the relative solids content in both feed and effluent. This served as a rapid and effective test on the degree of separation being obtained.

EFFECT ON FLOW PROPERTIES OF THE MUD

By reducing the volume concentration of the drilled solids, centrifuging lowers both the yield and plastic viscosity of weighted drilling muds.

Fig. 4 shows how operating the centrifuge for one day affected the plastic flow properties of 15 lb/gal. drilling mud on a Chocolate Bayou well, in Brazoria County, Tex., drilling at 12,000 ft. At this time, the centrifuge was processing about one-fifth of the mud in the circulatory system per day. Note that the yield point was lowered from 17.7 to 10.0 lb/100 sq ft and the plastic viscosity was reduced from 37.8 to 33.8 cp. By chemical treatment alone, the yield value is the only component of resistance to flow that can be reduced appreciably.

OTHER EFFECTS OF CENTRIFUGING

One of the chief values of the centrifuge in the treatment of muds lies in the continual maintenance of minimum viscosities. It is generally acknowledged that good flow properties contribute to better bottom-hole-cleaning action and consequent increase in rate of penetration.

With a centrifuge, a marked reduction in chemicals that are required for maintenance will result. In the Chocolate Bayou well on which the decanting centrifuge was tried, the quantity of chemicals used after centrifuging was initiated were only one-fifth that used prior to installation. The centrifuge was used while drilling from 11,800 ft to 14,600 ft.

TABLE 1 — RESULTS OF OPERATING DECANTING TYPE CENTRIFUGE AT VARIOUS SPEEDS AND WITH DIFFERENT WATER RATES WHEN CONCENTRATING DRILLING MUD FROM 12½ TO 22 POUNDS PER GALLON

Test No.	Centrifuge r.p.m.	Mud Density lb/gal.	Feed* Mud B/D	Feed* Water B/D	Spec. Grav. of Solids Sludge	Spec. Grav. of Solids Effl.	Total	Feed Solids lbs. per day Sludge	Feed Solids lbs. per day Effl.	**CLAYS Volume b.p.d. Total	**CLAYS Volume b.p.d. Sludge	**CLAYS Volume b.p.d. Effl.	**CLAYS Weight lbs. per day Total	**CLAYS Weight lbs. per day Sludge	**CLAYS Weight lbs. per day Effl.	**BARITE Volume b.p.d. Total	**BARITE Volume b.p.d. Sludge	**BARITE Volume b.p.d. Effl.	**BARITE Weight Total	**BARITE Weight Sludge	**BARITE Weight Effl.
1	1486	12.46	249	814	3.76	2.78	50,404	29,368	21,036	30.1	8.7	21.7	22,000	5,840	18,320	24.1	21.9	2.0	28,400	23,500	2,640
2	1470	12.47	285	698	3.78	2.87	71,249	48,580	22,669	32.9	9.84	22.5	29,996	9,230	18,249	28.5	26.4	2.74	41,253	39,350	4,421
3	1500	12.51	308	582	3.80	2.81	77,129	50,825	26,304	35.5	9.06	27.3	32,857	9,098	22,227	30.1	26.0	3.17	44,272	41,727	4,077
4	1736	12.46	328	814	3.79	2.75	75,328	46,693	28,635	40.4	10.7	31.0	32,617	8,592	25,771	33.4	29.8	2.16	42,711	38,101	2,863
5	1736	12.56	350	698	3.74	2.72	89,093	62,868	26,225	42.5	15.2	25.0	38,577	13,139	24,390	35.0	36.2	1.18	50,516	49,729	4,458
6	2070	12.37	405	814	3.67	2.67	100,249	71,225	29,024	50.7	18.05	36.1	45,531	17,521	28,414	38.7	34.9	.48	54,936	53,704	610
7	2070	12.32	395	698	3.64	2.66	89,752	62,325	27,427	53.3	20.2	32.9	44,591	16,329	27,152	35.6	35.8	.20	47,160	46,620	274

*Subsequent tests demonstrated that water rates shown in table were all in excess of that required for operation. High water volumes will lower separating effectiveness of this type of machine.

**All volume and weight calculations were derived from individual measurements on feed, sludge, and effluent. Good, but not exact correlation was obtained as reflected in the tabulated results.

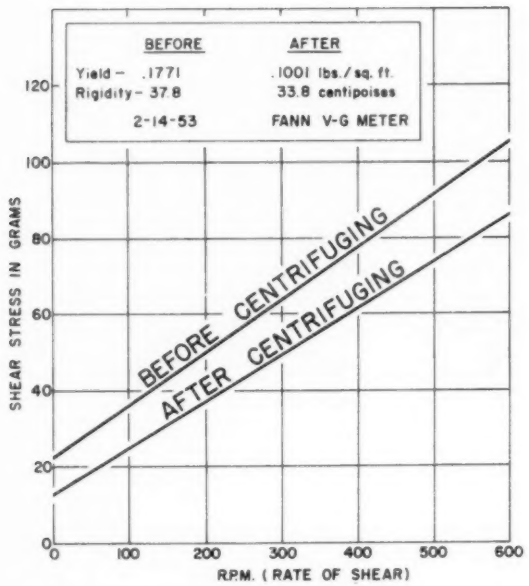

FIG. 4 — GRAPH SHOWING RESULTS OF 24 HOURS OF CENTRIFUGING 15 LB/GAL. DRILLING MUD ON PHILLIPS HOUSTON "T" NO. 1, CHOCOLATE BAYOU FIELD.

Much has been included in the literature on the effects of lime on high temperature gelation and high temperature solidification. Muds with high lime content will often solidify during drilling operations. Much more often, lime muds solidify when placed above the packer upon completion.

A centrifuge may be used to effectively remove a good portion of the active lime in a mud system upon completion. It may also make possible the drilling of deep wells without resorting to lime treatment.

Sand, being much coarser than other solid particles in the system, will readily settle in the first pit once the viscosity of the drilling fluid has been reduced by centrifuge action.

Upon completion of deep wells, the general practice is to abandon the contaminated mud remaining in the pits. A centrifuge may be used to clean-up, concentrate, and salvage a valuable portion of mud which otherwise would be discarded.

One phase of centrifuge performance that has not been evaluated, but which may be of importance, lies in the removal of "spent" chemicals from the mud. It is possible that part of the increase in viscosity which occurs with continued use of the mud is due to the accumulation of chemicals that have been added and whose effectiveness has been dissipated. By removing such chemicals the centrifuge will aid in maintaining low viscosity in weighted muds.

CONCLUSIONS

The practicality of a centrifuge for effecting substantial economies in drilling costs has been proved. The centrifuge will accomplish the following:

1. Maintain the desired flow properties of weighted drilling muds without resort to continual discarding and rebuilding substantial portions of the mud in the circulatory system;
2. Greatly reduce the quantity of chemicals required for treatment;
3. Reclaim and concentrate used muds to densities up to 24 lb/gal.

Properly installed and supervised, the machine will require little maintenance and attention.

Highly efficient separation may be obtained with the decanting type machine, resulting in low barite loss.

ACKNOWLEDGMENT

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PRESSURE MAINTENANCE by GAS INJECTION in the BROOKHAVEN FIELD, MISSISSIPPI

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ABSTRACT

The Brookhaven field is one of several Basal Tuscaloosa reservoirs located in south-central Mississippi. It is a standstone reservoir, of erratic deposition and with several faults, having an approximate subsea depth of 9,800 ft. A large variation in permeability exists with a weighted average being 256 md. Estimated average interstitial water saturation is 45 per cent. The undersaturated reservoir fluid exhibits marked differences in physical properties with measured saturation pressures ranging from 733 to 2,255 psi.

Early rapid decline in reservoir pressure caused the operating interests to unitize the field and initiate a program of pressure maintenance by gas injection. At the time gas injection was commenced, the reservoir pressure had fallen to nearly half of the original pressure with only 4.5 per cent of the original oil in place produced. The reservoir pressure has since been maintained at approximately 2,750 psig, and cumulative production to date is 17 per cent of original oil in place. An analysis of field performance during gas injection is presented in detail.

The program of pressure maintenance by gas injection is considered to be a success, since the expected ultimate recovery has been increased and the current production rate is in excess of 2 per cent of original oil in place per year. Performance has been better, anticipated ultimate recovery is larger, and total production costs are lower than for a similar Basal Tuscaloosa reservoir nearby, even though that field appears to have a more effective natural water drive.

INTRODUCTION

The history of the Brookhaven Unit is a testimonial for unitization and for the application of engineering techniques in the operation of an oil field. The operating and royalty interests in this field have mutually benefited from their early recognition of the need for unitization and pressure maintenance, and from the forthright manner in which these were accomplished. The tangible benefits accruing to the participants in the Unit are: (1) income from gasoline plant products, (2) reduced lifting and operating costs from those of competitive operation, (3) maintenance of high levels of current income by mitigation of the inevitable decline in production rates inherent to natural depletion, (4) an increase in ultimate recovery of about 40 per cent over natural depletion operations. This paper should properly be considered a progress report; however, the performance of the field after five years of pressure maintenance clearly indicates that the ultimate success of the project is assured.

LOCATION AND GEOLOGY

The Brookhaven field is located in south-central Mississippi, about six miles from the town of Brookhaven. Production at Brookhaven

[1]References given at end of paper.

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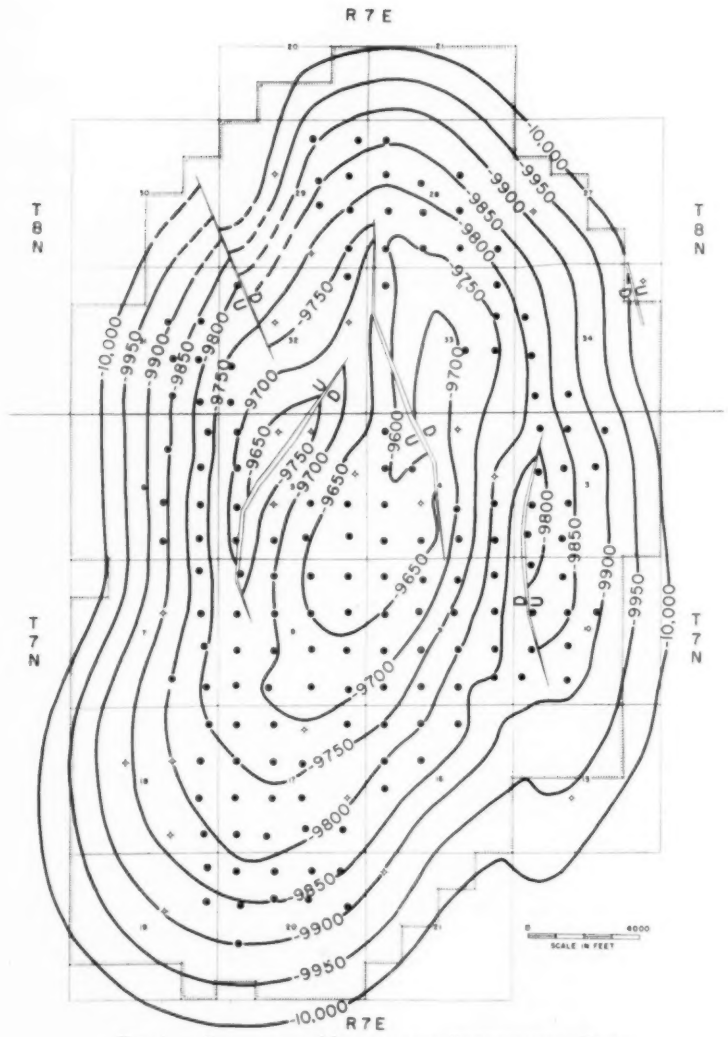

FIG 1 — STRUCTURE MAP OF THE BROOKHAVEN FIELD, LINCOLN COUNTY, MISS.

is from the Basal Tuscaloosa formation of Upper Cretaceous age. The average depth of the producing section is about 10,300 ft subsurface or 9,800 ft subsea.

Fig. 1 is the structure map of the field, drawn on top of the Basal Tuscaloosa formation. The proved closure is approximately 400 ft. Three faults trending north and south form a central graben area. The central of these faults occurs principally in a shaled out section of the field and is not of importance in the reservoir. The two faults along the east and west sides have sufficient throw to cause partial discontinuity within the reservoir. The erratic nature of the sand deposition is evidenced by two shaled out areas near the crest of the structure.

Production is from three separate zones in the Basal Tuscaloosa. These are the Pilot, Case and Smith zones. Fig. 2 shows two typical electric logs of the producing section with the general designation of these zones indicated. In the north and east portions of the field, the Smith and Case zones could not be readily segregated; therefore, these have been lumped together and called the Arrington zone. The Smith-Arrington zone has the greatest areal extent and is the major reservoir. Fig. 3 is the isopachous map of this zone. The Case zone has considerably less effective sand volume than the Smith, and the Pilot is relatively insignificant. Isopachous maps of these zones may be found in the literature.[3] The total effective sand volume is about 207,000 acre-ft, of which the Smith-Arrington zone comprises about 180,000 acre-ft and the Case zone 27,000 acre-ft.

DEVELOPMENT

The field was discovered by the drilling of The California Company's G. T. Smith No. 1. This well was completed as a small pumper in June, 1943. Two subsequent dry holes caused a period of inactivity until September, 1945, when Roeser and Pendleton's Leon Case No. 1 was completed as a good producer. This accelerated drilling activity and during 1946 and 1947 development was essentially completed on a 40-acre spacing. A total of 152 producers and 22 dry holes have been drilled in the field. Normal practice was to set about 1,100 ft of surface pipe and a production string of 7 or 5½-in. casing to total depth. The productive zones were then perforated. Many wells were initially completed in both the Case and Smith zones.

UNITIZATION

Early in the development period of the field frequent bottom hole pressure surveys were made. These surveys revealed that the reservoir pressure was declining at a very rapid rate. Only about 3,000 bbls of oil were produced per psi drop in reservoir pressure up to 1947. This clearly indicated that some form of pressure maintenance would be necessary to insure maximum recovery.

The operators held their first meeting in March, 1947. Plans were formulated for an engineering study of the reservoir. This study concluded that the limited natural water drive would not maintain pressure at a reasonable rate of production, so a program for unitization and pressure maintenance by gas injection was instigated. In June, 1948, only 15 months later, the unit agreements had been signed, a compressor plant built, a source of extraneous gas developed, and injection commenced in three wells. The California Co. is Unit operator.

Participation in production for both operating and royalty interests is based on the percentage of the total acre-feet of effective oil sand which underlies each tract. At the present time only one producing well in the field is not operated by the Unit. Approximately 98 per cent of the royalty interests have voluntarily signed the unit agreement.

The reservoir was originally undersaturated, and there was no extraneous source of gas in the field. Therefore, it was necessary to secure an outside source of gas to maintain pressure. A long-term contract was signed by the Unit with Southern Natural Gas Co. to supply the necessary make-up gas. Southern Natural laid a line from the Gwinville gas field, about 30 miles east of Brookhaven, to supply this gas. The contract guarantees a minimum purchase by the Unit of 11 MMcf per day for 12 years, and the average price is about 11 cents per Mcf. This gas is very dry, being composed of 97.5 mol per cent methane and 2.5 mol per cent carbon dioxide. A gasoline absorbtion plant was put in operation in June, 1949, together with a low pressure gas gathering system. These facilities are operated by the Unit.

RESERVOIR MATERIALS

The general drilling program included coring the Basal Tuscaloosa pay zones and analyses on cores from 140 wells were available. The average porosity of the Smith-Arrington zone is 26 per cent, and porosity of the Case zone is 24 per cent. The permeability of the Smith-Arrington zone ranges from 0 to 6,000 mds, and the arithmetic average is 340 mds. The arithmetic average permeability of the Case zone is 170 mds. Fig. 4 gives the permeability profile of a typical well. The permeability distribution as demonstrated by this typical profile would indicate that the coverage of injected gas may be very poor. However, layers of high permeability cannot be correlated from well to well, and it is postulated that this high degree of heterogeneity actually tends to improve the coverage by injected gas.

The average interstitial water saturation of the producing zone is estimated to be 45 per cent of the pore space. A transition zone with water saturation greater than 50 per cent occurs in the first 20-30 ft above the original oil-water contact.

Fig. 5 gives the two-phase, oil-gas, relative permeability data which have been used in the reservoir calculations. These curves represent the average of several laboratory investigations on Brookhaven cores and on similar Basal Tuscaloosa cores from neighboring fields.

The reservoir fluid was originally undersaturated, and there existed a unique condition with respect to fluid characteristics; that is, a variation in reservoir fluid properties within a more or less continuous reservoir. There were two very definite indications that this condition existed:

(1) Bottom hole sample analyses from seven wells at various locations within the field indicated a variation in saturation pressure from 733 psig to 2,255 psig.

(2) The gravity of the produced oil varied from 26° to about 40° API, and produced gas-oil ratios from 100 to over 500 cu ft/bbl.

For the purpose of making reservoir calculations, it was necessary to obtain data on the average fluid properties. This was accomplished by drawing a map of iso-saturation pressures, included as Fig. 6. The control for this map was obtained by plotting saturation pressure against both the produced tank oil gravity and GOR from the analyses of six wells sampled. (Fig. 7). Using this together with the well test data of produced gravity and GOR, a saturation pressure was estimated for each producing well not sampled. A weighted average saturation pressure of 1,439 psig was then estimated by planimetering this map.

The reservoir oil varies in viscosity from 0.6 to 1.9 cps. Fig. 8 gives the variation in formation volume factor and gas in solution with the saturation pressure. The formation volume factor of the original reservoir fluid varied from 1.155 to 1.375 and the gas solubility from 100 to over 500 cu ft/bbl. These curves have been extrapolated to calculated points at the current operating pressure. These points give the values of gas solubility and FVF of the saturated oil in the gas-swept formation under the assumption that injected gas goes in solution in the reservoir oil at the prevailing pressure, as discussed below.

PRESSURE PRODUCTION HISTORY

The pressure production history of the field is shown by Fig. 9. The reservoir pressure declined very rapidly from the original of 4,537 psig to slightly less than 2,800 psig in May, 1948, immediately prior to injection. The reservoir pressure has been maintained at between 2,700 and 2,800 psig by the gas injection program. The present distribution is shown by the iso-baric map of a pressure survey completed in October, 1952, Fig. 10. The two major faults and the two barren areas tend to restrict the over-all continuity of the reservoir. Therefore, to maintain

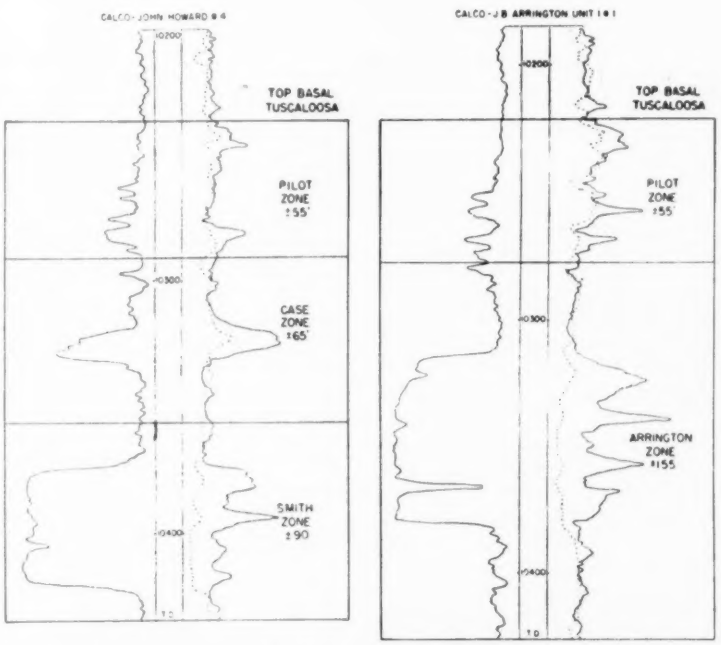

FIG. 2 — TYPICAL ELECTRIC LOGS OF PRODUCING ZONES IN BROOKHAVEN FIELD.

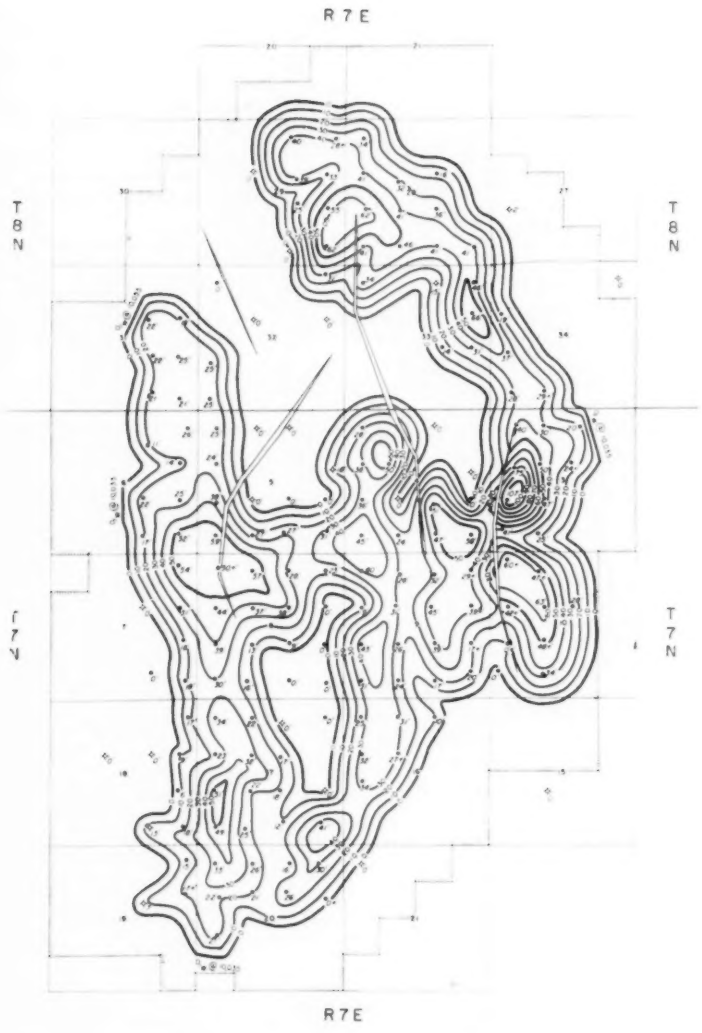

FIG. 3 — ISOPACH OF EFFECTIVE SAND, SMITH-ARRINGTON ZONE, BROOKHAVEN FIELD.

pressure in the entire reservoir, it has been necessary to inject in five dispersed areas. These areas are indicated on the isobaric maps. Presently, there are 12 injection wells, two in Block I, one in Block II, three in Block III, four in Block IV and two in Block V.

The production rate increased rapidly during the major development period, 1946 and 1947, and reached a maximum of slightly over 15,000 B/D in mid 1949. The production rate has declined somewhat from this maximum due principally to increasing gas-oil ratios and partially to water encroachment to edge wells. In recent months this decline has been arrested. The current production rate is approximately 12,000 B/D. This has been accomplished by installing additional compressor capacity, altering the stages of existing compressors and installing high pressure producing facilities in the field. The resulting increase in gas handling facilities permits the producing of wells after gas breakthrough.

The encroachment of edge water has imposed a secondary problem at Brookhaven. When water encroaches to a well the consequent lowering of the fluid level increases the lifting problem. This in itself is a serious problem, and at Brookhaven it is intensified by an apparent reduction in the total fluid productivity of the well. In most cases, there is as much as 50 or 60 per cent reduction in fluid productivity and in some cases complete plugging has occurred. In recent months, it has been found that these wells can be returned to a satisfactory producing status by the application of mud acid to increase fluid productivity and/or installation of gas lift valves to lift the necessary fluid volumes.

Currently about 37 MMcf per day is being injected. The initial gas gathering system was a 9 psig system. This sufficed as long as only solution gas was being produced, but after gas breakthrough occurred the volume of gas produced and tubing pressures increased. To handle this gas, 850 psig and 70 psig gathering systems have been installed. These systems are expanded as the gas front encroaches on additional wells. About 40 MMcf per day is currently being handled. Of this, 30 MMcf per day is compressed to 2,500 psig at the plant, including 11 to 13 MMcf per day of purchased gas, and about 10 MMcf per day is being compressed to 3,000 psig by three field compressors for direct discharge into injection wells. The plant processes about 18 MMcf per day of Unit gas and produces approximately 450 B/D of products. The cumulative gas injected through June, 1953, was about 39 billion cf. Fig. 11 shows the extent of the movement of injected gas from each of the five centers of injection as of Oct. 1, 1952.

The cumulative oil produced by the Unit wells through June, 1953, was 30,664,896 bbls. This represents about 17.5 per cent of the original oil in place, which was estimated to be 172.2 million bbls by volumetric calculations. Approximately 7.5 million bbls were produced prior to unitization and about 23 million bbls have been produced since the initiation of the gas injection program.

ANALYSIS OF PERFORMANCE

FACTORS AFFECTING PERFORMANCE

An analysis of the reservoir performance after five years of pressure maintenance by gas injection has been made. The purpose of this analysis was to determine how effective the gas injection program has been and from this estimate what the ultimate recovery will be. The analysis of the performance of this field is complicated by the following factors: (1) a wide variation in reservoir fluid properties, (2) a limited edgewater drive, (3) oper-

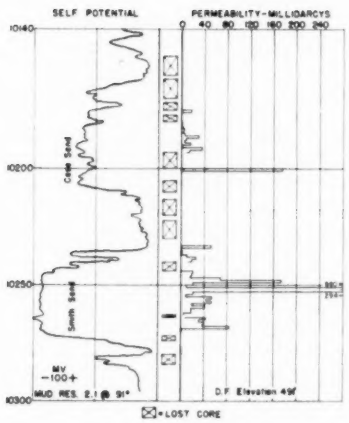

FIG. 4 — PERMEABILITY PROFILE OF A TYPICAL WELL, DANCIGER OIL AND REFINING CO. V. G. ALLEN NO. 2.

ating pressure considerably above the original saturation pressures of the reservoir oil, causing part of the injected gas to go into solution, (4) a tentative economic GOR limit for wells producing behind the gas front of 40,000/1, (5) a gravity gradient effective behind the gas front due to a slight formation dip, and (6) the geometry of the field.

In making an analysis of this type, there exists an inherent ambiguity. When oil is displaced, the resulting recovery can be attributed to: (1) high displacement efficiency from a small sand volume, or (2) low displacement efficiency from a large sand volume. In order to resolve this problem, it was necessary to employ both material balance and displacement type calculations to determine how much of the reservoir volume has been swept by gas and the recovery from this swept volume.

Due to its irregular geometry, the field is considered to be composed of five semi-independent reservoirs, as shown in Fig. 11. Gas is being injected in each of these Blocks. Because of this and the aforementioned complicating factors, a separate analysis has been made on each Block. For illustrative purposes only, the analysis of the Smith sand in Block IV is presented herein; this is believed to be representative of the field as a whole, because the performance of this Block during gas injection has been similar to the overall performance of the field. A detailed breakdown of production data from this Block and physical characteristics of the sand and reservoir fluids are given in Table 1. A brief summary of the analytical procedure employed is presented in the following paragraphs.

ANALYTIC PROCEDURE EMPLOYED

The Coverage Factor

"Coverage factor" is defined as the fraction of total effective sand behind the gas front which has been swept by gas. This should be distinguished from the "conformance factor" as presented by Patton,[3] which is the ratio of swept pore volume to the total reservoir pore volume. "Coverage factor" as herein used is a direct reflection of the reservoir performance at any stage of injection, whereas "conformance factor" by definition changes as the frontal position of the injected gas advances. First, the variation of the average free gas saturation with variation in coverage factor was calculated by material balance methods. Next, a relationship between coverage and average gas saturation was also established using Buckley-Leverett displacement type calculations.[4] The pair of values for these variables which satisfied both methods were accepted to be representative of reservoir performance.

The positions of iso-ratio lines, representing GOR's of 1,000/1, 5,000/1, 10,000/1, and 40,000/1, were estimated from the producing GOR's of the wells on Oct. 1, 1952 (the effective date of the analysis). These lines were superimposed upon a Smith sand isopachous map and the apparent reservoir volume enclosed by each was determined by planimetering. The position of the 1,000/1 GOR line was assumed to coincide with that of the gas front.

The Block under study was diagrammatically represented as in Fig. 12 where the Block is composed of two elements, B into which gas is being injected, and A into which edge water is encroaching. The boundary between B and A is the position of the gas front. By referring to the saturation pressure map, an average saturation pressure was determined for the fluids originally contained in each element. The physical properties of the reservoir fluids having these saturation pressures are given in Table 1. The hydrocarbon space in the gas-swept portions of element B contains free gas and saturated oil while the hydrocarbon space of the unswept portion of B contains undersaturated oil only. By material balance methods, the average free gas saturation in the swept portion of B was evaluated as a

TABLE 1 — SAND, PRODUCTION, AND FLUID DATA OF SMITH SAND, BLOCK IV, BROOKHAVEN FIELD

Sand Data:		
Porosity, ϕ	0.256	
Avg. Perm. K, md	256	
Interstitial water	0.45	
Total sand volume, acre-ft	55,445	
Sand volume enclosed by gas front, acre-ft	24,580	
Reservoir Temperature	250°F	
Production Data:	**Oil, Bbls**	**Gas, MCF**
Production prior to injection	2,404,263	
Production during injection period		
Wells ahead of gas front on 10-1-52	2,412,342	
Wells behind gas front on 10-1-52		
Prod. GOR's, GORs < GOR < 1000/1	1,852,466	802,131
1000/1 < GOR < 5000/1	436,497	1,105,748
5000/1 < GOR < 10,000/1	444,120	3,230,915
10,000/1 < GOR < 40,000/1	305,854	4,887,088
40,000/1 < GOR	2,035	195,517
Cumulative gas injected		14,008,782
Reservoir Fluid Data:	**Element B**	**Element A**
Beginning of injection,		
Reservoir pressure, 2,600 psig		
Saturation pressure	1,950	1,650
F.V.F. of oil, rvb/STB	1.304	1.273
Solution GOR, SCF/STB	433	...
On 10-1-52		
Reservoir pressure, 2,845 psig		
Saturation pressure, saturated oil	2,845	...
Undersaturated oil	1,950	1,650
F.V.F., saturated oil	1.402	...
Undersaturated oil	1.298	1.268
Solution GOR, saturated oil	647	...
Undersaturated oil	433	...
Gas conversion factor, rvb/MCF	1.2087	...
Viscosity @ 2,845 psig		
Saturated Oil, cp	0.540	
Gas, cp	0.019	

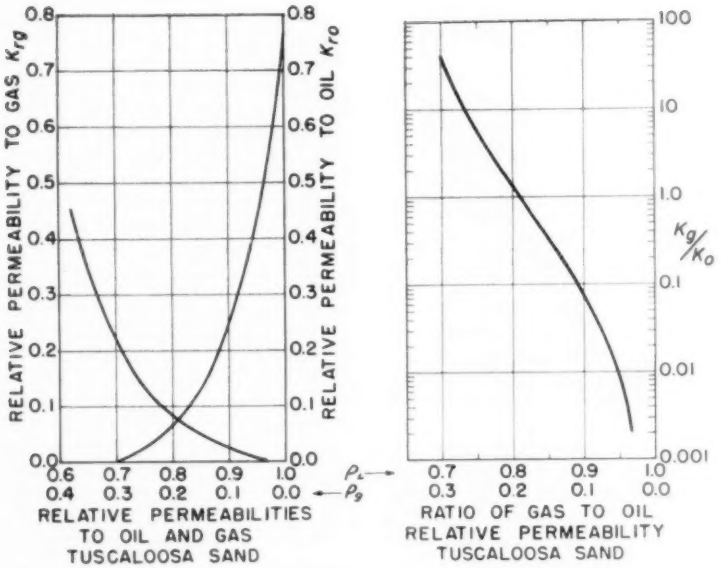

FIG. 5 — TWO-PHASE, OIL-GAS, RELATIVE PERMEABILITY DATA USED IN RESERVOIR CALCULATIONS.

function of the coverage factor, Fig. 13. The relationship of these variables may be expressed as,

1. $C_{\overline{P}_{cc}} = \dfrac{(1 - P_w)\, Q_{F_2} V_2}{N_{b1} \beta_{b1}}$

For the case where no injected gas is assumed to go into solution, Q_{F_2} is the net injected gas in the reservoir, or

2. (a) $Q_{F_2} = Q_{I_2} - Q_{P_2} + R_{b1} \triangle n_{b2}$

For the case where the oil remaining in the gas swept portion of *B* is considered to be fully saturated, the free gas is given by,

2. (b) $Q_{F_2} =$

$$\frac{(\beta'_{b2} - \beta_{b2})\ (Q_{I2} - Q_{P2} + R_{b1} \triangle n_{b2}) - (R_{b2} - R_{b1})\,[N_{b1}(\beta_{o1} - \beta_{b1}) + \beta_{b2}\,(\triangle n_{b2} + \triangle n_{I2} + \triangle n_{s2})]}{\beta'_{b2} - \beta_{b2} - V_2\ (R_{b2} - R_{b1})}$$

Where:

$\triangle n_{b2}$ = oil produced behind the gas front (cycled production).

$\triangle n_{I2}$ = Oil produced with its solution GOR from wells located behind the gas front.

$\triangle n_{s2}$ = Oil displaced from element B to element A.

(The remaining terms are defined in the legend at the end of this paper.)

By letting $\triangle n_{s2}$ have values progressively larger than zero, the curves, Fig. 13, were calculated. The two curves represent the limiting cases: (1) no injection gas goes into solution, and (2) the oil remaining in the swept pore volume is fully saturated at the prevailing pressure. It is believed that the latter is more representative of the actual situation.

In the normal Buckley-Leverett type displacement calculations where capillary pressure and gravity effects are ignored, the average gas saturation is solely a function of the volume of gas injected. However, if the gravity term in the equation is included,[5] the average gas saturation is also a function of the volumetric velocity, or flow rate. Since average distances between the iso-ratio lines could be measured on the flood map, application of a coverage factor resulted in reductions in the cross-sectional area available for transport. The flow rate resulting from any given injection rate is a function of the coverage factor. Consequently, the average free gas saturation in the swept pore volume could be evaluated as a function of the coverage factor.

Solving the Displacement Problem

In solving the displacement problem, a constant pressure of 2,845 psig was assumed. The average injection rate, in terms of reservoir gas volume, was calculated. Average volumetric velocities through each volume segment bounded by a pair of iso-ratio lines were determined by subtracting the cycled production from gross injection. For example, the reservoir volume produced with a ratio in excess of 10,000/1 was subtracted from the injected volume to find the fluid volume moving through that portion of the reservoir bounded by the 10,000/1 and 5,000/1 iso-ratio lines.

It was assumed that injected gas goes into solution at the gas front only. Having calculated the appropriate volumetric velocities for a given coverage factor, a series of fractional flow stream composition versus gas saturation curves were drawn. These were graphically differentiated and appropriate segments taken from each to construct the composite saturation distribution curve corresponding to a coverage factor of 0.55 given in Fig. 14. The discontinuities in the saturation distribution at the boundaries of the segments are the result of the assumption that the flow stream at an iso-ratio boundary is of constant fractional composition with respect to gas and liquid.

The average free gas saturation in each segment was directly calculated and from this the average free gas saturation in the entire gas swept portion of B determined. This procedure was repeated for various values of the coverage factor (Fig. 13). That coverage factor which yielded the same average free gas saturation in the swept portion of B using displacement theory and material balance methods was taken to be the most representative of the reservoir. It was found that an average free gas saturation of 15.3 per cent had been established in 55 per cent of the reservoir volume enclosed by the gas front.

Field Performance

Once a coverage factor had been established, a complete material balance solution on the Smith sand of Block IV was possible — including the cumulative net water influx during the period of gas injection. The oil production due to water encroach-

ment was related to the gross gas injected by the following procedure:

1. The variation of rate of water influx with time was calculated by a series of material balances, based on pressure and production data at various times during the injection period.
2. From the above and water production data, a plot of cumulative net influx versus time was made.
3. A plot of cumulative gas injected versus time was made from field data.
4. Cumulative net water influx was converted to stock tank oil and the desired relation was obtained by cross-plotting (2) and (3) above.

The difference between this curve and the actual performance curve for the Block is the performance of the gas injection program as illustrated in Fig. 15. The actual performance of the Block is described by the solid portion of Curve A. Curve C shows the oil recovery due to water encroachment and Curve B is the performance of the gas injection program as interpreted by the foregoing analysis.

Of interest is the degree with which the gas displacement performance as previously interpreted coincides with the theoretical performance of a comparable system. The theoretical performance may be readily calculated to any desired stage of depletion, and if applicable would permit estimates of the future performance of the Block to be made. Curves D and E are performance curves of this type and were calculated by the following methods.

Theoretical Performance

Electric model studies were made to determine the ultimate position of the gas front. They indicated that 71 per cent of the total Smith sand of Block IV would be enclosed by the ultimate front. Applying the previously established coverage factor to the pore volume enclosed by this front, the theoretical performance of Block IV was calculated, for the case of no production behind the front, after the method of Welge.[5] Curve D, on Fig. 15, describes the theoretical gas displacement performance of this case. The saturation distribution curve used in calculating this performance is the smooth curve in Fig. 14.

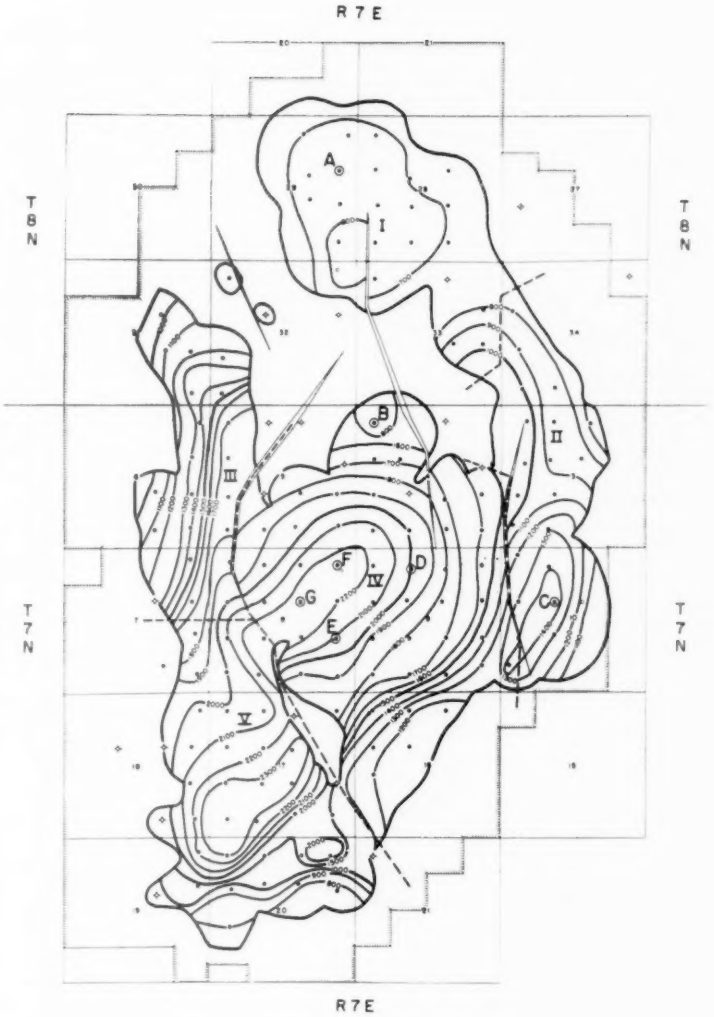

FIG. 6 — SATURATION PRESSURE MAP.

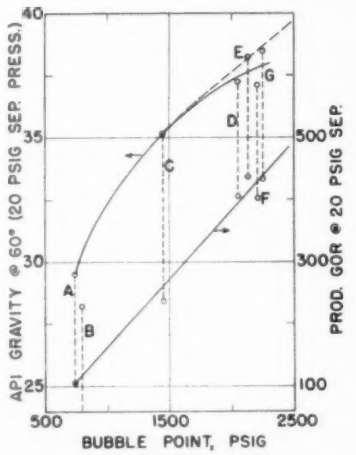

FIG. 7 — CORRELATION OF GRAVITY AND GOR VERSUS BUBBLE POINT OF BOTTOM HOLE SAMPLES.

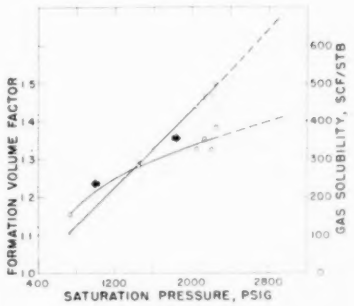

FIG. 8 — CORRELATION OF FORMATION VOLUME FACTOR AND GAS SOLUBILITY WITH SATURATION PRESSURE FOR SIX MEASURED BOTTOM-HOLE SAMPLES AT THEIR BUBBLE POINTS.

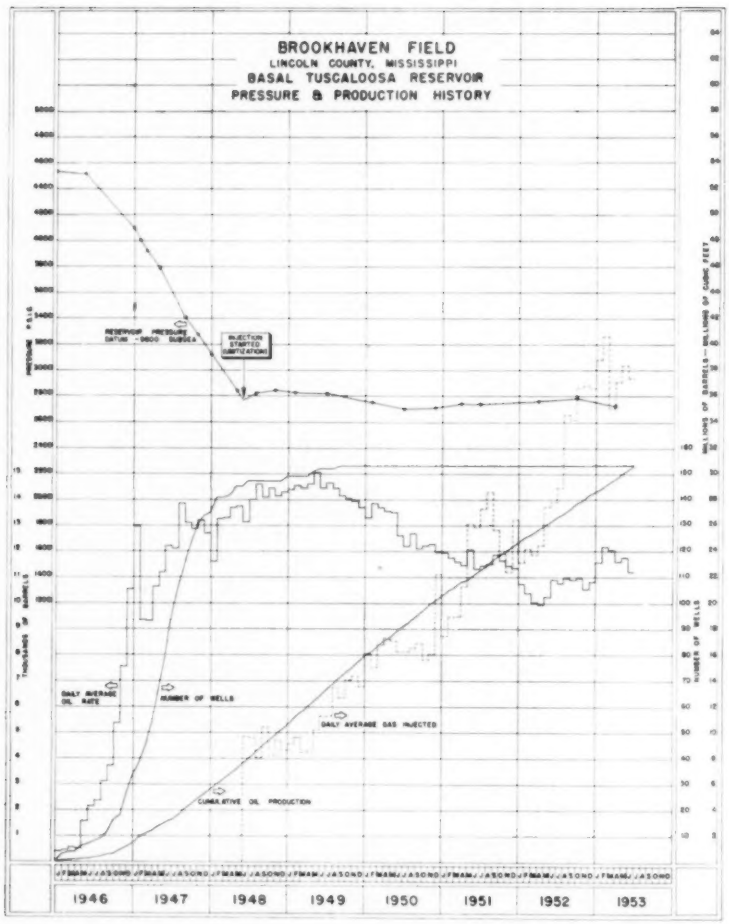

FIG. 9 — PRESSURE PRODUCTION HISTORY OF THE FIELD.

For the case where cycling occurs, the theoretical performance will not coincide with that indicated by Curve D because production behind the front will result in a more rapid increase in producing GOR. In order to calculate the behavior of a theoretical system representing an actual reservoir from which production is taken behind the advancing front of the displacing fluid, the plan or method of field operation must be known. Analysis of production data during the period of interest and the general principles guiding the operation of the field was, therefore, necessary. The plan followed to date at Brookhaven may be summarized as follows:

1. Those wells lying next to the boundaries of the Block have been produced continuously until their GOR's reached approximately 40,000/1. (with the exception of those wells lying near the edgewater boundary of the Block).
2. The interior wells have been produced until their GOR's reached 1,000/1. These wells have been shut-in, except for periodic testing, until their GOR's reached 5,000/1. After the producing GOR's reached 5,000/1, the wells have been opened and produced until their GOR's reached 40,000/1, consistent with the gas handling capacity of the plant. This procedure was adopted in an attempt to achieve a smooth gas front by reducing cusping into the producing wells. This cusping of gas into first line wells ahead of the gas front was indicated by the early behavior of the gas injection program.

Once established, this plan of operation was utilized with displacement theory to calculate the theoretical performance of the reservoir under cycling operations. The production, Table 1, was converted to reservoir volumes and average cycling rates determined. The procedure was to determine the injection volume necessary to cause the first ring of wells to produce with a ratio of 5,000/1 since this was the beginning of cycling.

The total reservoir volumes of the fluids produced with GOR's from 1,000/1 to 5,000/1, and 5,000/1 to 10,000/1, respectively, were divided by the time period during which cycling with these ratios took place. These rates were used to find that fractional part of the total flow stream which was produced behind the front. When the GOR of the first row of wells increased to 10,000/1, production in excess of this ratio became possible.

This procedure was repeated stepwise until production with ratios in excess of 40,000/1 became possible. The theoretical performance curve approximated in this manner is shown by Curve E in Fig. 15. The path taken by this curve depends upon the manner of operation of the field, since prior to breakthrough at the last row of wells any desired GOR may be achieved by judicious choice of producing wells. However, a mathematical consequence implied by the equations of Kern[6] is that if cycling occurs and all wells are produced to the same limiting GOR, the total amount of gas injected when the last row of wells produce with this GOR is the same as for the case without cycling. Consequently, the gas injection performance curves for the cycled and non-cycled cases join when the last row of wells produce with this ratio.

Estimated Gas Drive Production

If the coverage factor remains 0.55 and 39,303 acre-ft are ultimately enclosed by the 40,000/1 GOR line in this Block, an estimated 50 billion cu ft of gas will have been injected and 8.8 million stock tank bbls of oil will have been produced by gas drive. If the current rate of injection is maintained, it is estimated that the oil production due to water encroachment during the injection period will be 3.2 million STB. The total recovery from this Block during the gas injection period is, therefore, estimated to be 12 million STB, as shown by the extra-

polation of Curve A, Fig. 15. Since 2,404,263 STB of oil were produced prior to the initiation of gas injection, an estimated 31 per cent of the 46.45 million STB originally in place in this Block will have been recovered at the end of pressure maintenance. A total recovery of approximately 50 million bbls is estimated for the entire field.

The actual performance of the field indicates that the coverage factor has progressively increased to the present value of 0.55. Injection gas breakthrough to the first row of wells occurred after only a relatively small volume of gas had been injected. A coverage factor in the order of 0.40 was estimated at that time. Should future production provide data indicating that the coverage has continued on an increasing trend, it will be necessary to increase these recovery estimates.

The measurable performance of a reservoir is the combined result of all the producing mechanisms operable. Interpretation of performance data and delineation of production caused by each of these various mechanisms cannot be accomplished without resorting to the theory of each. Therefore, the interpretation of performance by gas displacement assumes that theoretical concepts and data used in applying these are valid. For example, if laboratory relative permeability measurements are not representative, the performance by gas displacement may be something other than that shown by Curve B. This paper merely attempts to point out that it is possible to interpret field data in the light of present theory. Also, that this interpretation reasonably agrees with the theoretical behavior of a hypothetical system having the parameters of the field.

GAS INJECTION VERSUS NATURAL DEPLETION

Fig. 16 shows a comparison of the calculated performance of the field under natural depletion with the performance estimated under gas injection operations. These estimates indicate that under pressure maintenance the ultimate recovery will be in the order of 50 million bbls or 250 bbls/acre-ft. This represents about 29 per cent of the original stock tank oil in place. The estimates of recovery by natural depletion indicate the ultimate recovery would be about 39 million bbls. However, the ultimate economic recovery under this method of operation is estimated to be 36 million bbls or about 21 per cent of the original oil in place. Under this method of operation, the decline in reservoir pressure would have required pumping from below 8,500 ft by 1957, and high lifting costs would have forced the abandonment of the field as uneconomic.

Fig. 17 is presented to show a comparison between the performance of Brookhaven, under gas injection, and a similar Basal Tuscaloosa reservoir which is being produced under natural depletion. This field, Mallalieu, is located about 12 miles from the Brookhaven field. The sand properties at Mallalieu are practically the same as those at Brookhaven, and the original reservoir oil was undersaturated. The principal difference between the two is that the Mallalieu west reservoir (for which the curve was drawn) is smaller than Brookhaven. The original stock tank oil in place was about 70 per cent of that at Brookhaven.

Actually, at Mallalieu production rates have declined to a point where pressure is being maintained above the bubble point by natural water drive. In spite of this, as shown by its performance curve, the production has rapidly declined to the present rate of only about 1 per cent per

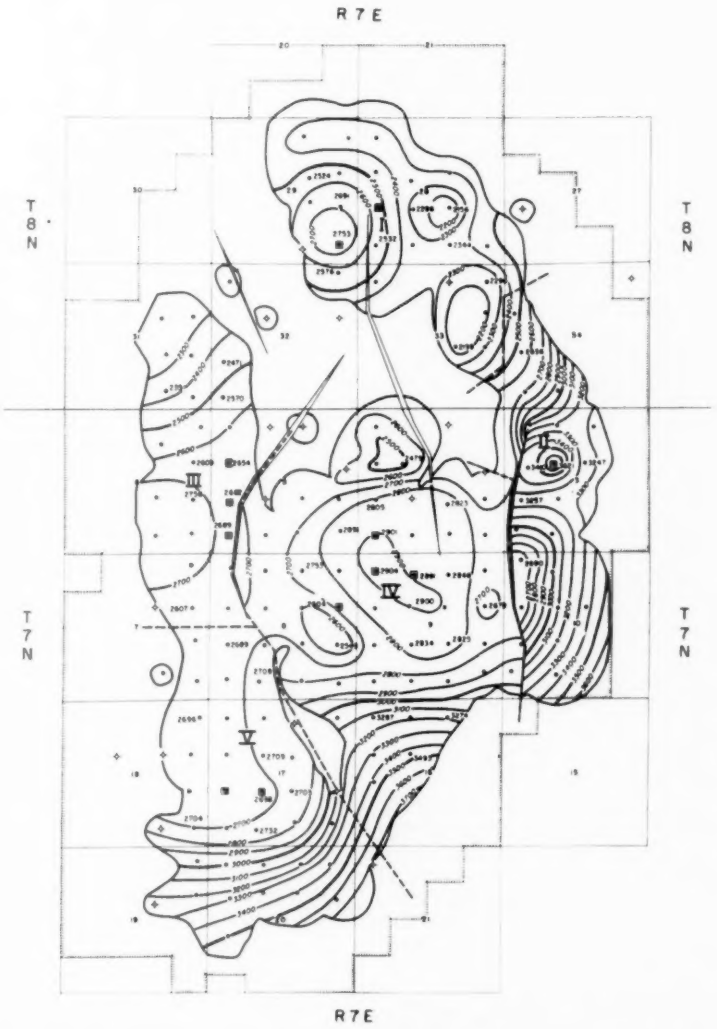

FIG. 10 — BOTTOM-HOLE PRESSURE MAP, OCTOBER, 1952. SUB SEA DATUM 9,800 FT.

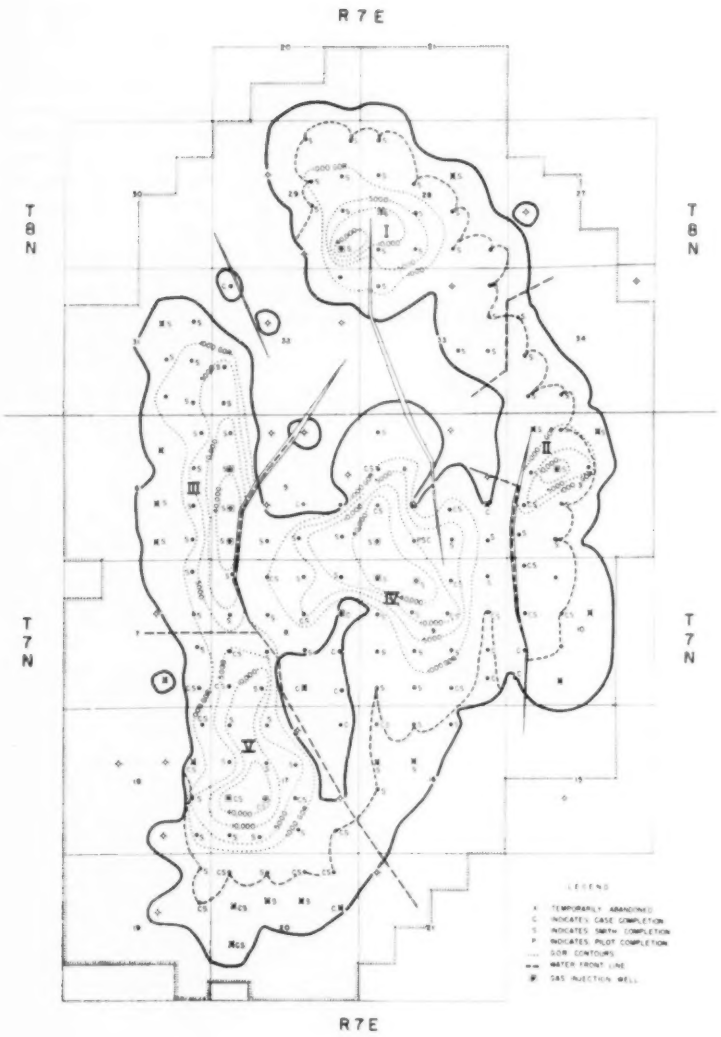

FIG. 11 — GAS AND WATER FLOODED AREAS.

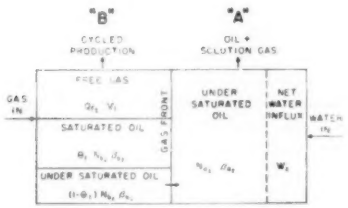

FIG. 12 — SCHEMATIC PRESENTATION OF BLOCK IV FOR MATERIAL BALANCE PURPOSES.

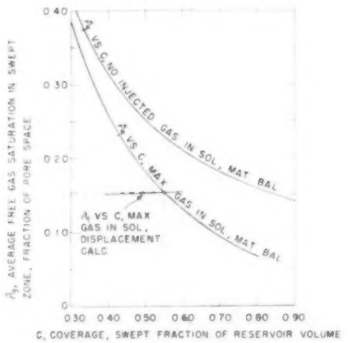
0.40
0.30
0.20
0.10
0
0.30 0.40 0.50 0.60 0.70 0.80 0.90
C, COVERAGE, SWEPT FRACTION OF RESERVOIR VOLUME
VS C, NO INJECTED GAS IN SOL., MAT. BAL
VS C, MAX GAS IN SOL., MAT. BAL
VS C, MAX GAS IN SOL., DISPLACEMENT CALC.

FIG. 13 — VARIATION OF AVERAGE FREE GAS SATURATION IN THE GAS-SWEPT PORTION OF THE RESERVOIRS WITH THE COVERAGE FACTOR.
Dotted line shows agreement between material balance and displacement calculations for the case where the oil in the gas-swept reservoir volume is fully saturated.

year of the original oil in place. An extremely long productive life will be necessary to recover a substantial part of the original reserve. The performance of Mallalieu is attributed principally to the fact that water encroachment to edge wells has caused their early abandonment. When water encroaches into a well, it is not physically possible to lift sufficient fluids from the low fluid levels to maintain economic production. The California Co. has found that lifting costs at Mallalieu are approximately one and one-half times those at Brookhaven, including the cost of purchased gas, which will have a resale value.

CONCLUSION

This paper has been presented as a progress report of five years of unitized pressure maintenance operations in the Brookhaven field. It should be stated that the performance during this period has been progressively better than the original predictions which furnished the basis for initiating the project. The overall economics have also been very satisfactory. Therefore, there is good basis for an optimistic outlook with regard to the future performance of the field.

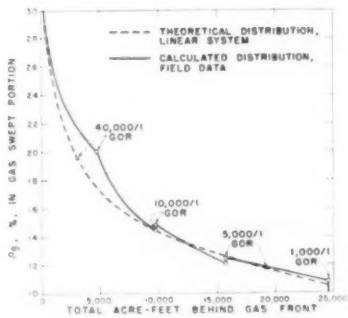

FIG. 14 — COMPARISON OF THE CALCULATED DISTRIBUTION IN THE GAS FLOODED REGION OF BLOCK IV WITH THE THEORETICAL SATURATION DISTRIBUTION RESULTING FROM GAS DISPLACEMENT IN AN IDEALIZED SYSTEM; NO PRODUCTION BEHIND THE GAS FRONT.

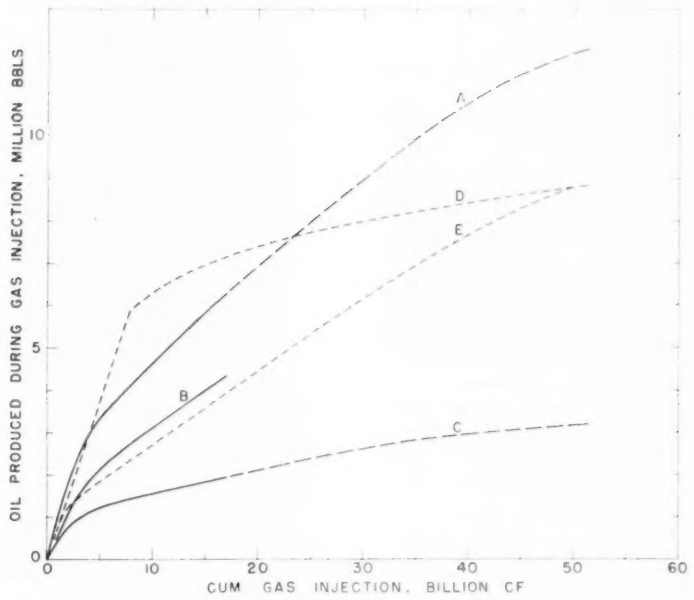

FIG. 15 — PERFORMANCE CURVES FOR THE SMITH SAND OF BLOCK IV.

A — Actual Performance, Measured Field Data.
B — Production Due to Gas Displacement.
C — Production Due to Water Encroachment.
D — Calculated Performance, No Cycled Production.
E — Calculated Performance, Production Behind Gas Front.

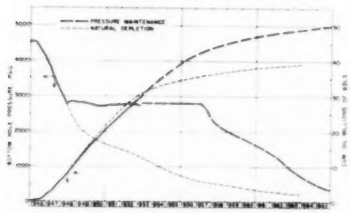

FIG. 16 — COMPARISON OF ESTIMATED CUMULATIVE OIL RECOVERY AND RESERVOIR PRESSURE DECLINE UNDER NATURAL DEPLETION AND PRESSURE MAINTENANCE OPERATIONS.

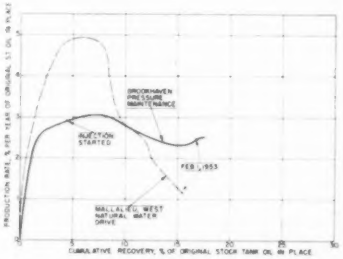

FIG. 17 — COMPARISON OF PERFORMANCE OF TWO SIMILAR BASAL TUSCALOOSA RESERVOIRS UNDER DIFFERENT PRODUCTION SCHEMES: (1) MALLALIEU, WEST RESERVOIR — NATURAL WATER DRIVE AND PRESSURE DECLINE CONTROLLED BY WITHDRAWAL RATES; AND (2) BROOKHAVEN — PRESSURE MAINTENANCE BY GAS INJECTION.

LEGEND

Numerical subscripts indicate different times.

Subscripts, a and b, refer to position relative to the location of the 1,000/1 GOR contour line.

Primes indicate different fluid systems; e.g. β_b, β_b'.

β = Formation volume factor, rvb/STB

R = Solution, GOR, SCF/STB

W = Net water influx into reservoir, bbls

C = Coverage, fraction of total hydrocarbon space swept behind the front.

N = Oil in place in one portion of reservoir, STB

Δn = Incremental oil production from one portion of reservoir, STB

ϕ = Fractional porosity

Q_t = Cumulative gas injection, MCF

Q_F = Free gas in reservoir, MCF

Q_b = Total gas produced behind gas front, MCF

$\bar{P}_c$ = Average gas saturation behind front, swept zone

P_{wc} = Connate water saturation, fraction of pore space

θ = Fraction of reservoir oil behind front absorbing injected gas

V = Reservoir volume occupied by 1.0 MCF S.C. gas, rvb

ACKNOWLEDGMENT

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Proration and Unitization Discussed by Dallas Groups

The faults of proration and the legal aspects of unitization were subjects discussed by Dallas groups at recent meetings.

"What's Wrong with Proration" was the topic of a talk by William J. Murray before approximately 70 members and guests. Murray, of the Texas Railroad Commission, discussed the basis used to compute the total oil allowable, MER's, market demand determination, and the division of the total state allowance among the various fields.

"Legal Aspects of Field Wide Unitization" was the subject discussed by the study group. Discussion leader was Dwight L. Simmons, of the law firm of Thompson, Wright & Simmons, Dallas.

Wide Variety of Subjects Presented Before Sections At March, April Meetings

A wide variety of subjects were covered at local section meetings in March and April, according to reports received in the Petroleum Branch offices.

The Fort Worth Section presented a talk by Herman H. Kaveler, Tulsa consultant, on "Advice to the Apprentice." Don Pendery, International Business Machine Corp., and T. D. Mueller, California Research Corp., were scheduled to speak on "The Operation and Application of Electronic Computers to Oilfield Reservoir Problems" at the San Joaquin Valley Local Section meeting.

"Methods of Stimulating Production" was the title of a paper presented at the Denver Petroleum Section meeting by W. E. Hassebroek. The East Texas Section showed a 37-minute movie on "Rotary Drilling Fluids."

March meetings featured Harold Vance, vice-president of the Second National Bank, Houston, speaking on "Oil and Gas Loans" before the Gulf Coast Local Section. Bruce Grant presented a paper on "Development of an Underground Heat Wave for Oil Recovery" at the North Texas Local Section meeting.

At New Orleans the Delta Section Study Group and Local Section meetings both produced good attendance in March. The Local Section group heard Leander H. Perez, District Attorney for St. Bernard and Plaquemines Parishes, speak on "Tidelands and State Boundaries." "Dual Completion Practices" were discussed by the Study Group, with Webb Jay and George Dausch, Jr., Southern Natural Gas Co., as moderators.

Jim Story of the V. E. Kuster Co. and Edward A. Scown of HOMCO of California spoke on the subject of bottom hole surveying at the March meeting of the Pacific Petroleum Chapter Junior Group.

Site Set for 1957 AIME Meeting

New Orleans will be the scene of the 1957 annual meeting, the dates being February 25 to 28. This is the week preceding the Mardi Gras celebration.